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EVALUATION OF REFORMULATED THERMAL CONTROL COATINGS IN A SIMULATED SPACE ENVIRONMENT

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13. ABSTRACT *(Maximum 200 words)*

The Air Force Space and Missile Systems Center and Wright Laboratory Materials Directorate (WL/ML) sponsored an effort to reformulate and qualify Illinois Institute of Technology Research Institute (IITRI) spacecraft thermal control coatings.

S13G/LO-1, Z-93, and YB-71 coatings were reformulated by IITRI because the potassium silicate binder, Sylvania PS-7, used in the coatings is no longer manufactured. Coatings utilizing the binder's replacement candidate, Kasil 2130, manufactured by The Philadelphia Quartz (PQ) Corporation, Baltimore, Maryland, were tested at the Materials Directorate's Space Combined Effects Primary Test and Research Equipment (SCEPTRE) Facility operated by the University of Dayton Research Institute (UDRI). The SCEPTRE Facility's simulated space environment consists of combined ultraviolet (UV) and electron exposure with *in situ* specimen reflectance measurements. A brief description of the effort at IITRI, a brief description of the SCEPTRE Facility, results and discussion from testing of the reformulated YB-71, S13G/LO-1, and Z-93 coatings in SCEPTRE and other organizations are presented.

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FOREWORD

This technical report, "Evaluation of Reformulated Thermal Control Coatings in a Simulated Space Environment," documents the results of some of the work performed under United States Air Force Contract No. F33615-90-C-5963, "Fluids, Lubricants, Coatings, and Elastomeric Materials," over the period 3 March 1993 to 7 August 1995. The results of testing which was conducted to requalify the Illinois Institute of Technology Research Institute (IITRI) spacecraft thermal control coating materials, YB-71P, S-13GP/LO-1, and Z-93P are presented.

The USAF Project Engineer on this program was Mr. Patrick S. Carlin, WL/MLBT, Wright-Patterson AFB, Ohio.

1. INTRODUCTION AND BACKGROUND

The exterior surfaces of all spacecraft are covered with a combination of insulation and thermal control coatings to regulate the internal temperature of the spacecraft. This temperature depends on the internally generated heat of the spacecraft, the heat absorbed from the sun, and the heat radiated out to space. Insulation prevents heat from the sun from entering the spacecraft, but also prevents heat from escaping. Therefore, areas of the exterior surface must be exposed to space to allow radiation of excess heat. These areas, called radiators, are coated with thermal control coatings that allow radiation of thermal energy while reflecting most of the incident solar energy. The thermal balance of the spacecraft is determined by the solar absorptance (α_S) and the thermal emittance (ε) of this surface coating. Usually, the thermal control coatings are chosen to provide the lowest possible absorptance and the highest possible emittance, for a minimum α_S/ε ratio. In addition, the coatings must be easy to apply, durable, low outgassing and stable in the space environment.

Zinc orthotitanate (Zn_2TiO_4, a.k.a., ZOT) and zinc oxide (ZnO) pigmented coatings are commonly utilized on spacecraft because of their optical properties and stability to the space environment. Three state of the art thermal control coatings, Z-93, YB-71 and S13G/LO-1, supplied to industry by IITRI, incorporate potassium silicate as a major and vital component in their composition. Potassium silicate is manufactured using elevated temperatures and pressures to generate specific molar ratios of K_2O and SiO_2 (ref. 1) and is purchased in solution form. Upon drying, the potassium silicate becomes a mixture of primarily K_2O and SiO_2, with other various silicates of potassium ($K_2Si_2O_5$, K_2SiO_3, $K_2Si_4O_9 \cdot H_2O$, and $KHSi_2O_5$) theoretically present.

In the case of ZnO pigmented S13G/LO-1, which uses a silicone binder, the potassium silicate is used to reactively encapsulate the ZnO pigment particles. This allows for the formation of a barrier to photodeposition reactions on the surface of ZnO and enhances the space stability of the coating. In the case of the inorganic ZnO pigmented Z-93 and ZOT pigmented YB-71, the potassium silicate constitutes the binder in the coatings. The potassium silicate used in the formulation of white spacecraft thermal control coatings, Z-93, YB-71, and S13/GLO-1, was manufactured by Sylvania as PS-7 potassium silicate solution. Sylvania discontinued the

manufacture of PS-7, which threatened the continued availability of these coatings to AF space systems. To ensure the continued supply of these thermal control coatings, WL/ML began a contracted effort with IITRI (points of contact: Yoshiro Harada and Mukund "Mike" Deshpande) in October of 1991 to reformulate and qualify new versions of Z-93, YB-71, and S13G/LO-1 with an alternate and available binder system. The Air Force Space and Missiles Systems Center (SMC) sponsored this contractual effort and Jerry Bauer and Michael Meshishnek of The Aerospace Corporation provided technical guidance to the Materials Directorate.

IITRI identified The PQ Corporation's Kasil 2135 potassium silicate solution as an ideal replacement material for the Sylvania PS-7. The Kasil 2135 had better purity levels than the PS-7, but production of the Kasil 2135 is only performed on limited research levels, thus it was not considered a viable alternative. The PQ Corporation indicated that production of Kasil 2130 would be continued indefinitely. Since Kasil 2130 has identical SiO_2:K_2O mole ratio of 3.3:1 as PS-7 and similar purity levels, viscosity, and other properties, IITRI chose it as the candidate replacement binder early in their effort. IITRI used Kasil 2130 to reformulate the coatings, performed various processing and properties evaluation studies, and demonstrated that Kasil 2130 is a suitable candidate material to replace PS-7 in the three thermal control coatings. ITTRI designated the reformulated coating candidates as Z-93P, YB-71P, and S13GP/LO-1. IITRI's efforts were documented in a Wright Laboratory technical report (ref. 2).

The final aspect of the program involved testing of the coatings in a simulated space environment and comparing the results to the original formulation coatings. Space simulation tests of these materials have been conducted at various facilities. These include: UV & electron exposure testing at WL/ML's SCEPTRE facility (ref. 3 & 4) and at The Aerospace Corporation (ref. 5); vacuum ultraviolet (VUV) and atomic oxygen exposure testing at both NASA Lewis and NASA Marshall; and UV, electron, and proton exposure testing at NASA Marshall (ref. 6). Additionally, the Canadian Space Agency flew samples of the candidate coatings in the "Materials Exposure in Low Earth Orbit (MELEO)" experiment on STS-52. The results of this spaceflight experiment was that all exposed samples showed no optical or physical degradation. IITRI submitted coating samples to The Aerospace Corporation for flight testing on the Ballistic Missile Defense Organization (BMDO) sponsored Space Active Modular Materials Experiment

(SAMMES) flight experiment which was designed to directly measure solar absorptance and hemispherical emittance using calorimetric techniques. Unfortunately, the Pegasus launch vehicle malfunctioned and was destroyed during launch. The second attempt at flying this experiment, SAMMES II, is scheduled to launch in early 1998 (ref. 7).

The purpose of this study was to determine the performance of the old and new formulations of the IITRI coatings in a multiple radiation environment consisting of high vacuum, low energy electron, and UV radiation.

2. SCEPTRE DESCRIPTION

WL/ML's Space Combined Effects Primary Test Research Equipment (SCEPTRE) Facility is the only Air Force owned facility designed specifically for testing and qualification of spacecraft thermal control coating materials (ref. 8). Testing at the facility is performed in accordance with the guidelines established by the American Society for Testing and Materials (ASTM) *E 512-94 Standard Practice for Combined, Simulated Space Environment Testing of Thermal Control Materials with Electromagnetic and Particulate Radiation* (ref. 9). The system has the capability of providing synergistic UV and electron radiation environments similar to those experienced by satellites orbiting in mid-to-high earth orbits and is shown in Figure 1. In addition, the system has the ability to perform *in situ* measurements of sample temperature and reflectance as a function of wavelength. The vacuum level is maintainable from approximately 6.7×10^{-6} to 6.7×10^{-5} Pa (5×10^{-8} to 5×10^{-7} Torr), the sample temperatures can range from room temperature to 100°C (212°F), the simultaneous multiple sun levels average between 1.0 to 3.0 equivalent ultraviolet suns (EUVS) (250-400 nm), and the electron flux is adjustable to a maximum of 10^{12} $e^{-}/cm^{2}/sec$ at energies adjustable to a maximum of 20 KeVs, for each of the two electron guns. This combination of specifically tailored parameters provides an accelerated testing environment with synergistic effects of vacuum, accelerated UV and electron radiation, and limited thermal cycling.

2.1 Vacuum System

The vacuum system is composed of a 45.72 cm (18 in) diameter belljar pumped by a Welch Vacuum Technology model 3106S turbomolecular pump, backed by a Welch Vacuum Technology model 1397 rotary pump. The chamber is monitored via two different ion gages, a Granville-Phillips 271 Series and a Fredricks-Televac model 3C5-2A2; and a Uthe Technology Inc. (UTI) model 100C residual gas analyzer. The chamber has the capability of exposing a maximum of five, 2.38 cm (15/16 in) diameter, specimens to the synergistic UV and electron radiation. Figure 2 shows the facility's sample wheel, containing five white thermal control coating specimens, positioned just below the Faraday cup. The specimens are indirectly cooled via a chilled water line. The temperature control system reduces the temperature of the exposed specimens by approximately 5.56°C (10°F).

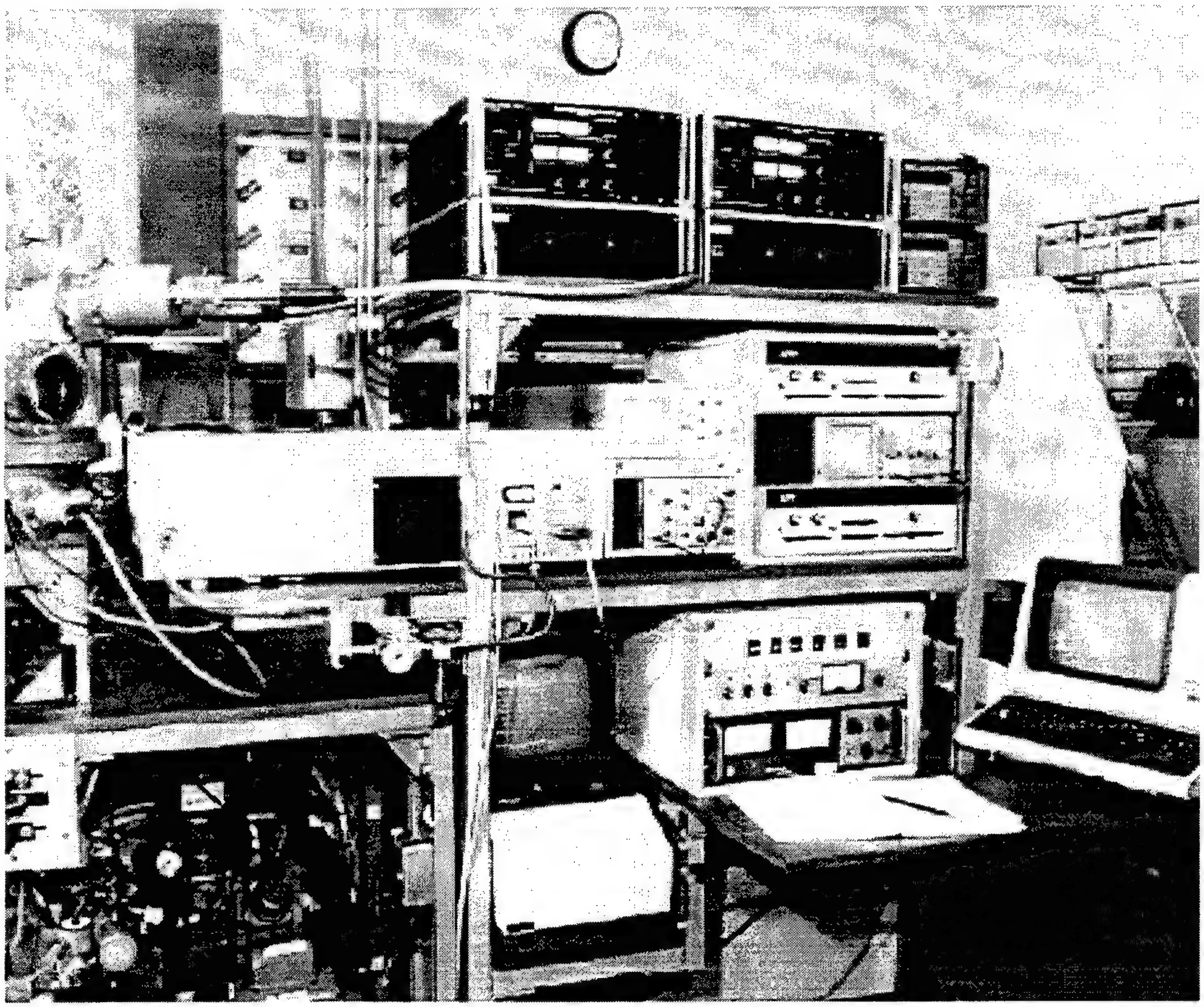

Figure 1. USAF WL/ML SCEPTRE Facility.

2.2 Solar Simulator

The solar simulator consists of a moderately filtered 2500 Watt xenon arc lamp mounted in a modified Spectrolab X-25 solar simulator. The entire optical system of the Spectrolab X-25 has been replaced and redesigned by the University of Dayton Research Institute. The xenon arc lamp is nominally filtered and is capable of generating 6 EUVS and has a non-uniform intensity distribution across the beam's profile, with the center of the beam being more intense than the edges. The output of the solar simulator is measured with an EG&G model 580 spectroradiometer that is calibrated using an EG&G 1000 Watt quartz-tungsten-halogen FEL

style lamp (250-1100 nm) traceable to the National Institute of Standards and Technology (NIST) data.

2.3 Electron Guns

The SCEPTRE Facility utilizes two Kimball Physics Inc. EFG-11 electron guns. These guns are designed to provide a flood of electrons with energies ranging up to 20 KeV. Their output are monitored by a Faraday cup situated 6.98 cm (2.75 in) above the center most sample position (see Figure 2). A Keithley 617 programmable electrometer is used to measure the electron current generated by the Faraday cup. The electron beam is adjusted using a phosphor screen and determined to be relatively uniform across the specimens.

2.4 Spectrophotometer

The spectrophotometer used to monitor the specimens' solar absorptance is a Perkin-Elmer Lambda 9 UV-Vis-NIR double beam spectrophotometer and is fiber-optically coupled to a Labsphere Inc. integrating sphere located inside the vacuum chamber. The spectrophotometer is designed to provide *in situ* NIST traceable reflectance measurements and is utilized periodically throughout the duration of a test.

2.5 Data Acquisition

The data acquisition is performed by a Digital Equipment Corp. (DEC) VAXstation III/GPX, in conjunction with hardware from a variety of other vendors, and utilizes IEEE-488, RS-232, analog-to-digital, and digital-to-analog interfaces. The system monitors the electron flux, vacuum level, specimen backside temperatures, and residual gases present in the vacuum chamber every 15 seconds and periodically records the data throughout the duration of a test. It also acquires data from the spectrophotometer and spectroradiometer and is used to analyze and graphically display the data.

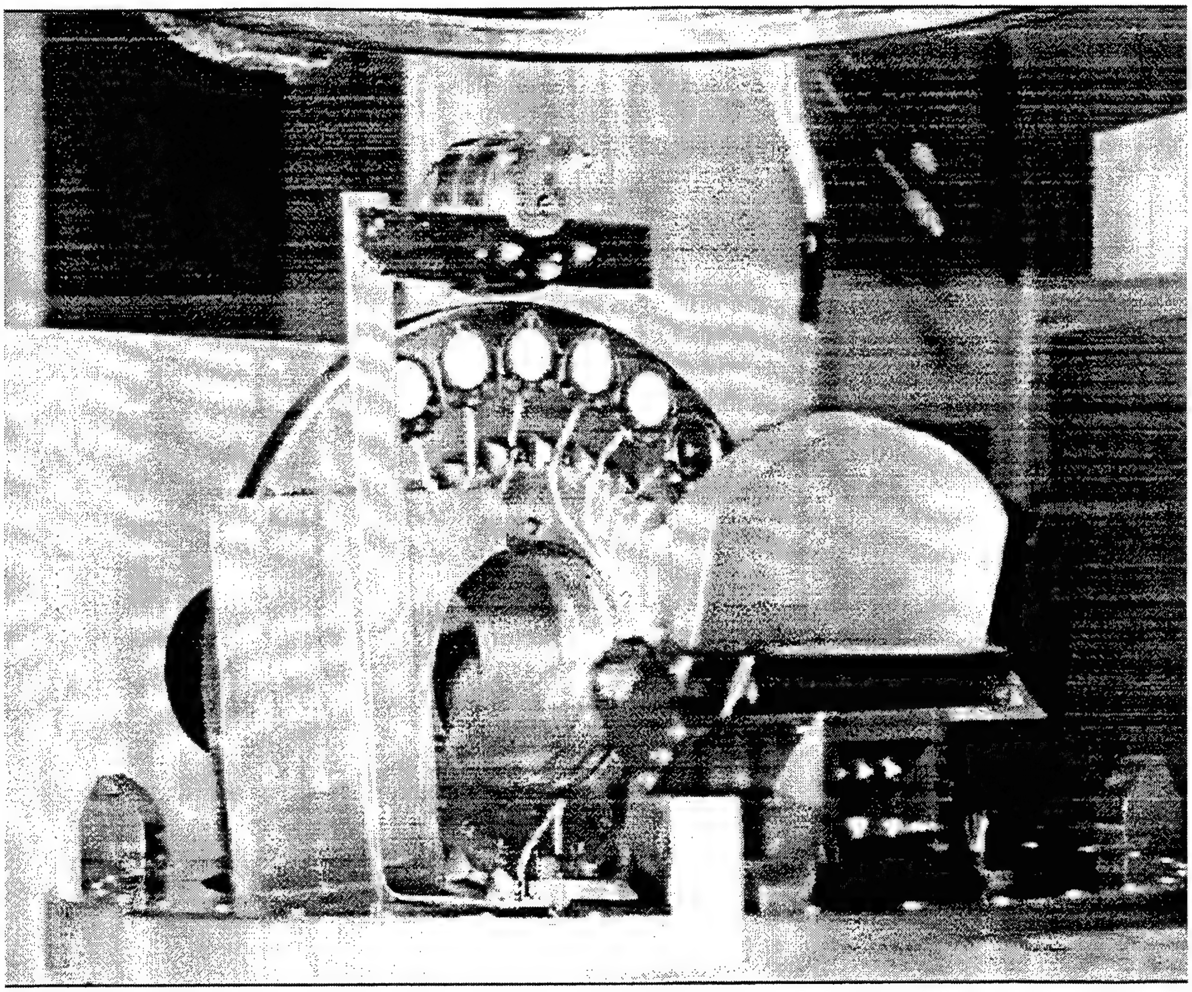

Figure 2. USAF WL/ML SCEPTRE Facility Sample Wheel.

3. SCEPTRE TESTING

Due to the limited number of specimen locations and the symmetric distribution of the UV radiation exposure, the most informative practice for testing materials in the SCEPTRE facility is to limit the number of different materials tested to two. This provides a direct comparison between four of the specimen locations by exposing two specimens of each material to very similar environments. The fifth specimen location, the center location, provides a unique exposure environment relative to the other four locations. The SCEPTRE testing program for the new formulations of the IITRI materials was intended to directly compare the old and new materials in the SCEPTRE simulated space environment. This testing program required that three SCEPTRE tests be performed, one for each of the different coating materials. Additionally, extra Z-93 specimens were used as controls in the center location for direct comparisons between the three tests necessary for the reformulated IITRI materials. Each of the tests was planned to have 1000 hours of exposure with accelerated UV and electron radiation. The targeted UV levels for the five samples were: 3.0 EUVS for the Z-93 control specimen in the center location and two specimens of each of the new and old formulations of the materials each receiving 2.5 and 1.0 EUVS. The electron exposure was arranged to provide accelerated low energy electron radiation compared to that experienced in geosynchronous orbits.

For the two electron guns that the facility has, energy levels of 1 KeV and 10 KeV were chosen. At the geosynchronous orbits there are both trapped and solar wind electrons. The AE8-MAX trapped electron model (ref. 10) and data originating from the SCATHA space flight experiment (ref. 11) were used in establishing the values of 3×10^9 $e^-/cm^2/sec$ for the 10 KeV electrons and 6×10^9 $e^-/cm^2/sec$ for the 1 KeV electrons. At 1000 hours of exposure this would generate a total fluence of 3.24×10^{16} e^-/cm^2. Reference 10 indicates that the fluence of solar plasma electrons within the energy range of 0-10 KeV would be 5.8×10^{15} e^-/cm^2 in a 1000 hour period, therefore the acceleration factor for the electron exposure is 5.5.

3.1 Tests 93QV01 & 93QV02

The testing program, as described above, called for three different SCEPTRE tests, one for each of the different IITRI coatings. The first IITRI materials to be tested would be YB-71

and YB-71P. They were tested in SCEPTRE test number, 93QV01. However, the results from the first 93QV01 test were so disturbing that a second test, 93QV02, was necessary to either substantiate or refute the results from the first test.

The 93QV01 test was performed from 3 March to 29 April 1993. The first 600 hours of the 93QV01 test proceeded very well. However, at 602 hours into the test, a power outage occurred that lasted approximately 40 minutes. This power outage caused a temporary loss in vacuum (estimated to be 1.0×10^{-3} Pa (7.5×10^{-3} Torr)) and ultimately caused the electron gun filaments to burn out. The test was continued to 1000 hours of exposure with UV radiation only. The performance of the YB-71P material was very disappointing. Very early in the test it was obvious that the YB-71P material was not performing nearly as well as the YB-71. Figure 3 shows the results of the simulated space environment on all the Z-93, YB-71, and YB-71P specimens' solar absorptance. All data in this graph were obtained by *in situ* reflectance measurements, except the last data points, which were measured within a few hours after exposure to air. These results were not satisfactory and created a lot of concern about the reformulated coatings.

Synergistic atomic oxygen and VUV exposure testing performed at NASA Lewis (ref. 12), had showed Z-93P to be a poor performer on one occasion. These results also generated a lot of concern, so the Z-93P was re-tested with a specimen from a different batch of material. The re-test found the problem to be isolated to the specific batch of coating tested. For this reason it was thought that there might be a similar problem with a batch of the YB-71P. Since both the poor performing Z-93P (tested at NASA Lewis) and the poor performing YB-71P (tested with SCEPTRE) were made with the same lot of Kasil 2130, it was decided to re-test the YB-71 and YB-71P in SCEPTRE. The second test, number 93QV02, exposed a YB-71 specimen, a YB-17P "bad batch" (IITRI batch no. R028) specimen (which had been used as a vacuum only reference in the 93QV01 test), two YB-71P specimens from a different batch (IITRI batch number S038), and a Z-93 cross-reference specimen.

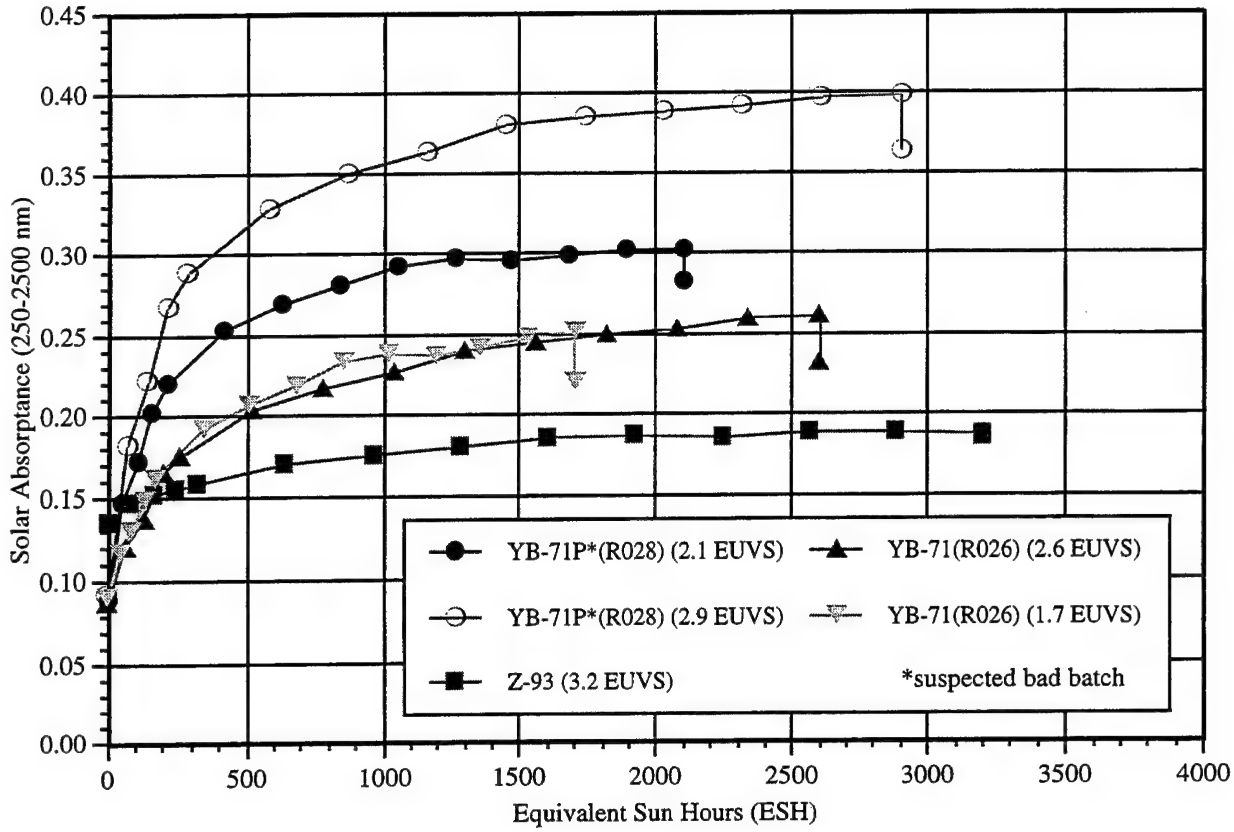

Figure 3. SCEPTRE Test 93QV01 for YB-71 & YB-71P Materials.

Performance of the second test was affected due to optical alignment problems within the solar simulator. The situation limited the unobscured UV exposure to three sample positions while the two outer-most positions were exposed to an unknown amount of gradient shading. Thus, the cross-reference Z-93 specimen was not used in the same position as the 93QV01 test and only three specimens: the YB-71, YB-71P (suspected bad batch), and YB-71P (new batch), were exposed to known UV levels. The UV exposure of the second YB-71P (new batch) and the Z-93 cross-reference specimens were not discernible, but were estimated to be about 1.0 EUVS.

The retest of YB-71P, SCEPTRE test 93QV02, was performed from 16 December 1993 to 24 February 1994. The 93QV02 test showed that there was a difference in performance of the two different batches of YB-71P. Figure 4 shows the comparison of the YB-71 and YB-71P performance during the 93QV02 and 93QV01 tests. As previously mentioned for the 93QV01 data, all the 93QV02 data points were measured in vacuum, except the last three points which

were measured in air over a period of 12 days. This figure shows that the new YB-71P can perform identically to the old YB-71 material and verifies the repeatability of results for like materials from different SCEPTRE tests. Histories for the 93QV01 and 93QV02 tests, including electron flux, specimen backside temperature, vacuum chamber pressures, vacuum foreline pressure, and all specimen (including controls) reflectance spectra data are included for reference in Appendices A and B. Note that in these figures, the suspected bad batch (IITRI batch no. R028) of YB-71P is labeled with an asterisk (YB-71P*). A summary of the test environments and solar absorptance data for each specimen, from both tests, is provided in Table 1.

As mentioned above, both the extent and rate of solar absorptance "recovery" were different in each of the tests for similar materials. The difference can only be attributed to the fact that after the second test, 93QV02, the specimens were not directly brought back to ambient conditions but the vacuum chamber was first purged with gaseous nitrogen prior to atmospheric exposure. This resulted in the specimens taking more than 12 days to recover only a fraction of their reflectance instead of essentially recovering instantaneously as they did in the 93QV01 test, without the nitrogen purge. It can be assumed that the gaseous nitrogen molecules, while not chemically reacting with the materials, did physically block access of the oxygen atoms to the material and restricted the rate and even extent of the oxygen recombination process that restores some of the material's reflectance properties.

Visual inspection of the specimens revealed that the old formulation of YB-71 tested in the 93QV02 test had a non-uniform, "blotchy" pattern of light and dark areas within the coupon. The poorer performing specimens from both tests exhibited more crazing (or micro-cracking) due to the shrinking associated with the loss of moisture from the materials than did the other specimens. The poorer performing specimens also exhibited a small amount of adhesion loss near the edges of the coupon.

3.1.1 XPS Analysis

Several weeks after the completion of the 93QV01 test, surface analysis (X-ray Photoelectron Spectroscopy, XPS) was performed on the exposed YB-71P specimens, using a Surface Science Instruments apparatus which utilizes a monochromatic X-ray source and charge

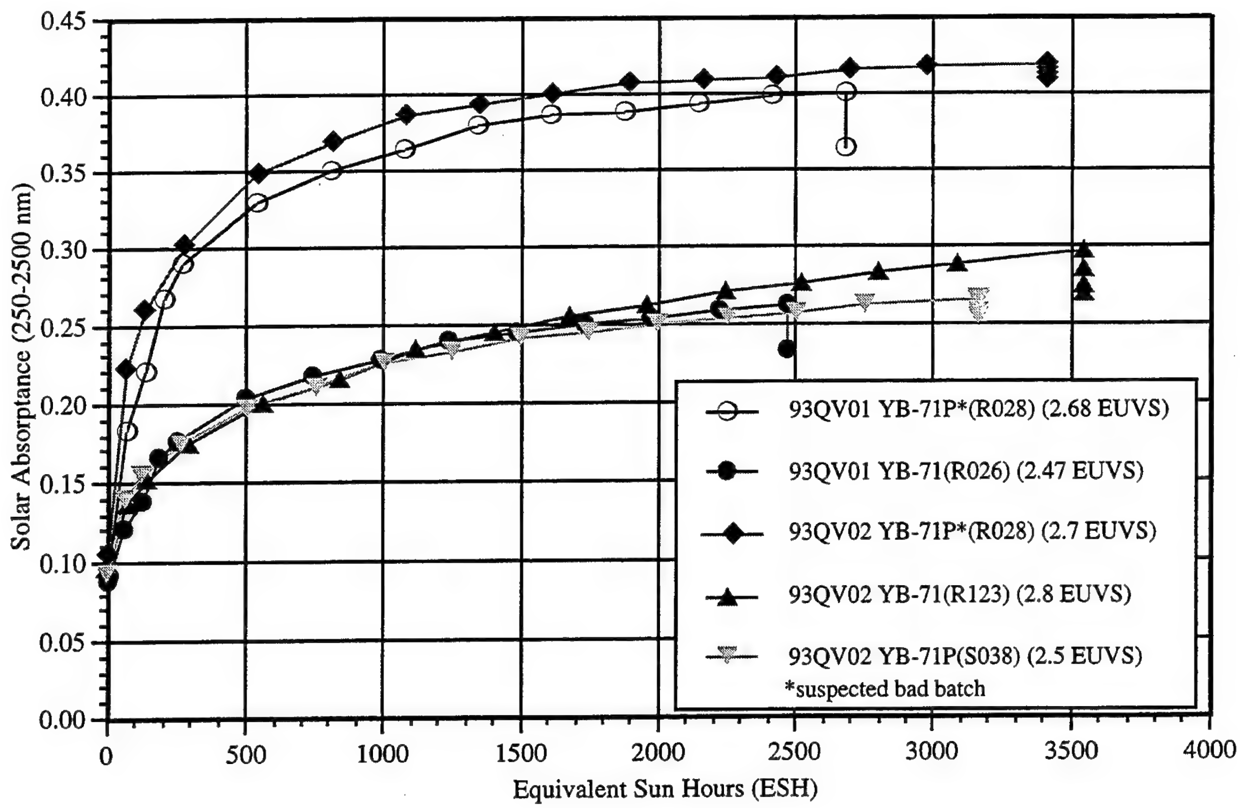

Figure 4. Comparison of SCEPTRE Tests 93QV01 & 93QV02 for YB-71 & YB-71P.

neutralization, to determine if their poor performance was due to contamination. The XPS did reveal a slight amount of carbon but not enough to attribute to significant amounts of contamination.

Prior to the 93QV02 test, XPS was performed on a YB-71 specimen (which ended up being used as a reference in the 93QV02 test) and a YB-71P specimen from the suspected bad batch (which was exposed in the 93QV02 test) that showed a difference between the composition of the YB-71 and the YB-71P materials. The suspected bad batch (IITRI batch no. R028) YB-71P specimen contained more potassium than did the YB-71 specimen. The difference was measurable but initially not thought significant.

TABLE 1

SUMMARY OF SCEPTRE TESTS 93QV01, 93QV02, 94QV01 AND 95QV01

Material	IITRI Batch No.	Specimen Number	EUVS (250-400 nm)	1 KeV fluence (e-/cm2)	10 KeV fluence (e-/cm2)	Pretest solar absorptance (in vacuum)	Posttest solar absorptance (in vacuum)	Change in solar absorptance (in vacuum)
93QV01 (1000 hrs.)								
Z93	R009	MM-10	3.2	1.7E+16	8.3E+15	0.135	0.185	0.050
YB-71	R026	MM-1	2.6	1.7E+16	8.3E+15	0.087	0.232	0.145
YB-71	R026	MM-3	1.7	1.7E+16	8.3E+15	0.090	0.220	0.130
YB-71P*	R028	IITRI-42	2.1	1.7E+16	8.3E+15	0.089	0.282	0.193
YB-71P*	R028	IITRI-40	2.9	1.7E+16	8.3E+15	0.092	0.363	0.271
93QV02 (1265 hrs.)								
Z93	R009	MM-11	1.2 (est.)	2.0E+16	1.0E+16	0.134	0.178	0.044
YB-71	R123	C-017	2.8	2.0E+16	1.0E+16	0.097	0.297	0.200
YB-71P*	R028	IITRI-45	2.7	2.0E+16	1.0E+16	0.106	0.419	0.313
YB-71P	S038	X-5	2.5	2.0E+16	1.0E+16	0.093	0.266	0.173
YB-71P	S038	X-6	1.1 (est.)	2.0E+16	1.0E+16	0.097	0.233	0.136
94QV01 (1369 hrs.)								
Z-93	R009	MM-12	3.0	3.0E+16	1.5E+16	0.136	0.225	0.089
S-13G/LO-1	Q090	MM-1	2.3	3.0E+16	1.5E+16	0.165	0.380	0.215
S-13G/LO-1	Q090	MM-3	0.9	3.0E+16	1.5E+16	0.165	0.306	0.141
S-13GP/LO-1	R055	MM-75	2.4	3.0E+16	1.5E+16	0.161	0.296	0.135
S-13GP/LO-1	R055	MM-75	0.9	3.0E+16	1.5E+16	0.165	0.255	0.090
95QV01 (1140 hrs.)								
Z-93	R115	A-019	2.5	2.9E+16	1.4E+16	0.132	0.201	0.069
Z-93P	R120	A-118	2.1	2.9E+16	1.4E+16	0.128	0.195	0.067
Z-93P	R120	A-117	1.7	2.9E+16	1.4E+16	0.124	0.183	0.059
Z-93P	U151	FR-19	2.4	2.9E+16	1.4E+16	0.127	0.201	0.074
Z-93P	U151	FR-20	1.8	2.9E+16	1.4E+16	0.123	0.187	0.064

*suspected bad batch

After the 93QV02 test, all three exposed YB-71 and YB-71P specimens and the exposed Z-93 specimen were examined with the XPS analysis. This analysis showed that both the YB-71 and new batch of YB-71P contained about 12.5% potassium while the "bad batch" (IITRI batch no. R028) of YB-71P contained about 20% potassium. The Z-93 specimen showed the smallest amount of potassium of any of the IITRI materials analyzed so far. This is interesting because, this material was shown to be the best performer in the 93QV01 test. Additionally, the light and dark areas of the "blotchy" areas previously discussed on the YB-71 used in the second test were separately examined with XPS. The results of this analysis are extremely interesting because it showed that in the old formulation of YB-71, with the Sylvania

PS-7 binder, that the light areas contained 13.6% potassium and the darker areas contained 17.9% potassium. While the XPS analysis suggests that there is direct link to the coating's performance and its potassium concentration at the surface similar XPS measurements performed at The Aerospace Corporation (ref. 5) did not show this correlation and in fact, contradicted the USAF WL/ML XPS results. Table 2 summarizes the XPS results.

3.1.2 Results and Discussion

The reflectance spectra for all the poor performing YB-71P specimens (see Appendices A and B), while showing total overall reduction in reflectance, also show a depression in the reflectance curve around 950 nm that is more pronounced than in the YB-71 specimens. This absorption band, which is characteristic of Zn_2TiO_4, is discussed in detail in a 1971 American Institute of Aeronautics and Astronautics (AIAA) paper authored by Zerlaut, *et al.* (ref. 13). This paper describes the Ti^{+3} color center formation damage mechanism for

TABLE 2

SUMMARY OF XPS RESULTS

Material	K	Si	K:Si Ratio	Change in solar absorptance (in vacuum)
<u>93QV01 (1000 hrs.)</u>				
YB-71P* (2.85 EUVS)	22.2%	9.2%	2.41	0.271
YB-71P* (2.07 EUVS)	21.0%	9.8%	2.14	0.193
<u>93QV02 (1265 hrs.)</u>				
YB-71P*				
pretest	20.3%	9.9%	2.05	*****
posttest (2.70 EUVS)	20.4%	9.9%	2.06	0.313
Z93 (1.2 EUVS, est.)	12.3%	22.1%	0.56	0.044
YB-71P (2.50 EUVS)	12.6%	16.0%	0.79	0.173
YB-71 (2.80 EUVS) (darker area)	17.9%	12.0%	1.49	*****
YB-71 (2.80 EUVS) (lighter area)	13.6%	15.8%	0.86	*****

* suspected bad batch

Zn_2TiO_4 and presented findings which showed that reactively encapsulating the Zn_2TiO_4 with potassium silicate greatly reduces the extent of damage around 950 nm. The fact that the YB-71P coating is demonstrating a depression in the reflectance curve similar to that described in the paper is very interesting and presently unexplainable.

The inconsistency of the potassium silicate binder is a cause for concern. Similar testing of YB-71 and YB-71P materials from the same batches tested in SCEPTRE have been performed at The Aerospace Corporation, El Segundo, California which revealed similar results for the materials' optical stability.

Additional attempts at finding a replacement for the Sylvania PS-7 potassium silicate for use in other coatings, have been made by researchers at the Jet Propulsion Lab (JPL). They tried to identify a suitable conductive coating for use on the Cassini satellite's high gain antenna system and considered the NS43G coating (obtained from Space Control Coatings, Inc.), using both the PS-7 binder and the Kasil 2135 binder from The PQ Corporation as a possible candidate (ref. 14).

The 93QV01 and 93QV02 testing of IITRI's YB-71 material presented the rare opportunity to directly compare the results of ground-based, simulated space environment testing to actual on-orbit flight performance testing. In the late 1970s and early 1980s, IITRI's YB-71 (a.k.a., zinc-ortho titinate, ZOT) was used in spaceflight experiments flown in geosynchronous orbits. The solar absorptances of these specimens were measured using calorimeters and the data was telemetered back to earth. This data was used to measure the change of solar absorptance versus time (actually, equivalent sun hours). Figure 5 shows the data for two of these flight experiment specimens (ref. 15) with the results from the SCEPTRE Facility on the same material, YB-71. With the exception of the difference in the beginning of life solar absorptance values, both the rate and extent of solar absorptance degradation are very similar between the ground-based and spaceflight experiments. IITRI was asked about the difference in the beginning of life solar absorptance values for the materials, they indicated that the difference could be due to some differences in the material from being manufactured over 10 years apart or just solar absorptance measurement differences. Irrespective of the beginning of life solar absorptance differences, the direct comparison of SCEPTRE data to spaceflight data

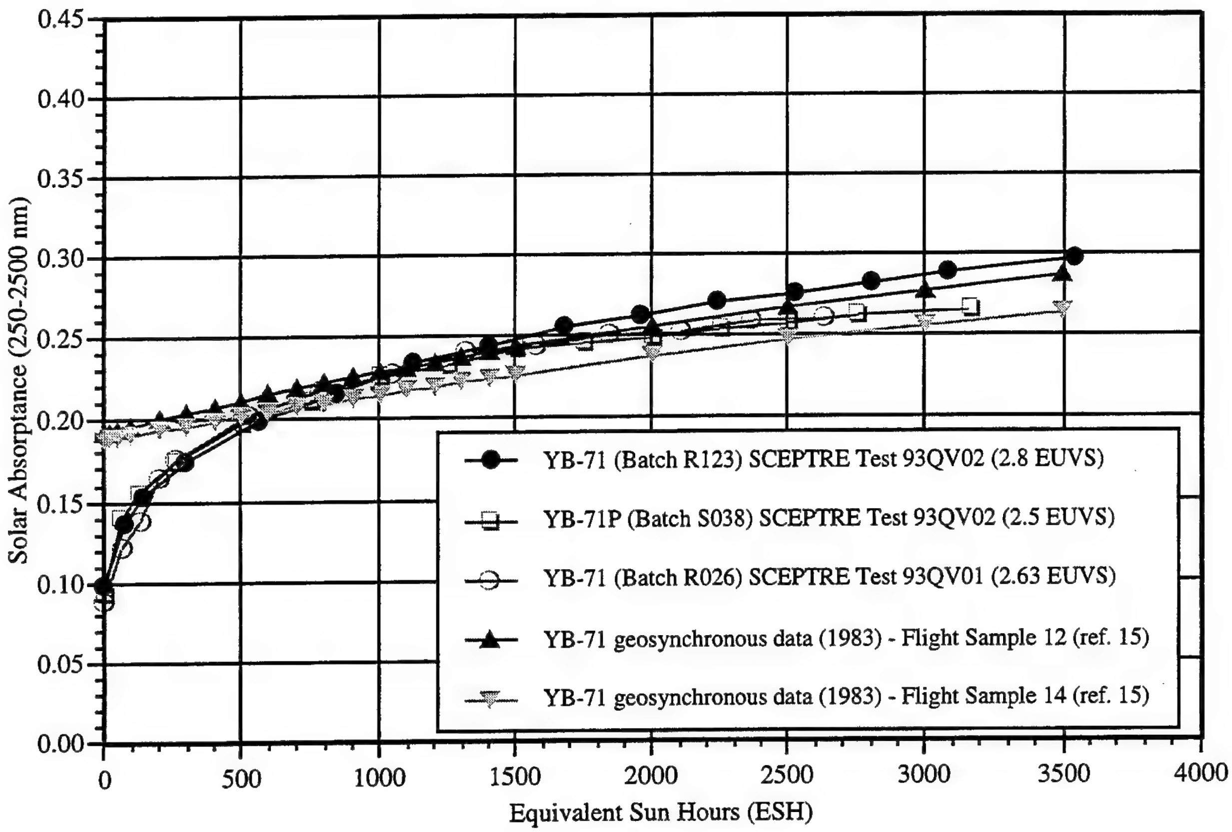

Figure 5. Comparison between SCEPTRE and 1983 Spaceflight Data for YB-71.

substantiates the appropriateness of the SCEPTRE Facility and its testing practices as a tool for evaluating spacecraft thermal control materials in geosynchronous orbits.

3.2 SCEPTRE 94QV01 Test

The 94QV01 test of the IITRI S-13GP/LO-1 coating was conducted from 12 September 1994 through 28 November 1994, with electron only and recovery experimentation continuing into January 1995. The test consisted of 1295 hours of synergistic UV and electron exposure for the specimens and an additional 74 hours of electron only exposure on the test specimens. The test results are summarized in Table 1 by showing the environment seen by each specimen along

with the specimen's pretest, post-test, and change in solar absorptance (250-2500 nm) values. Execution of the test was uneventful with the exception of a xenon arc lamp explosion 341 hours into the test. This event was not detrimental to the overall goal or function of the test but did produce some interesting results. The resulting replacement of the lamp and necessary realignment procedure interrupted the exposure of the specimens for 9 days. Before the synergistic exposure was continued the specimens were exposed to UV radiation only for 47 hours to adjust the exposure levels to what was initially intended, after which the test was resumed as normal.

The change in solar absorptance for the specimens throughout the duration of the test is shown in Figure 6. This figure indicates that S-13GP/LO-1 outperformed S-13G/LO-1 in the SCEPTRE simulated space environment. The new coating outperformed the old one by 28% for the higher (2.3 - 2.4 EUVS) exposure level and 20% for the lower (0.9 EUVS) level.

Visible inspection of the specimens was made immediately following exposure to atmospheric conditions. The S-13G/LO-1 specimen (IITRI specimen no. MM-1), exposed to 2.3 EUVS, had a very non-uniform "blotchy" or "mottled" appearance and "cracked" pattern of dark lines, while all other specimens seemed to have a uniform light brown appearance, typical of the S-13G/LO-1 material. After the visual inspection was performed, the chamber was closed and the post-test-in-air reflectance scans were performed. Several days later the chamber was once again opened and the specimens were re-examined. This time the non-uniformly damaged S-13G/LO-1 (IITRI specimen no. MM-1) had disappeared and the specimen now had a very uniform brownish appearance similar to the rest of the S-13G/LO-1 and S-13GP/LO-1 specimens.

After the lamp exploded, the specimens received electron only exposure for 47 hours before the situation was discovered. Figure 6 shows (at the ESH values associated with the 341 hrs. of exposure for each of the specimens) a marked increase in the rate of degradation in all specimens after the electron only exposure incident but the change is especially dramatic in the Z-93 specimen. Discussions with Mr. Dave Edwards of NASA Marshall revealed (ref. 16) that they had seen similar behavior for the Z-93 material. At that point it was decided to perform experimentation, at the end of the formal test (i.e., the conclusion of all normal exposures), to

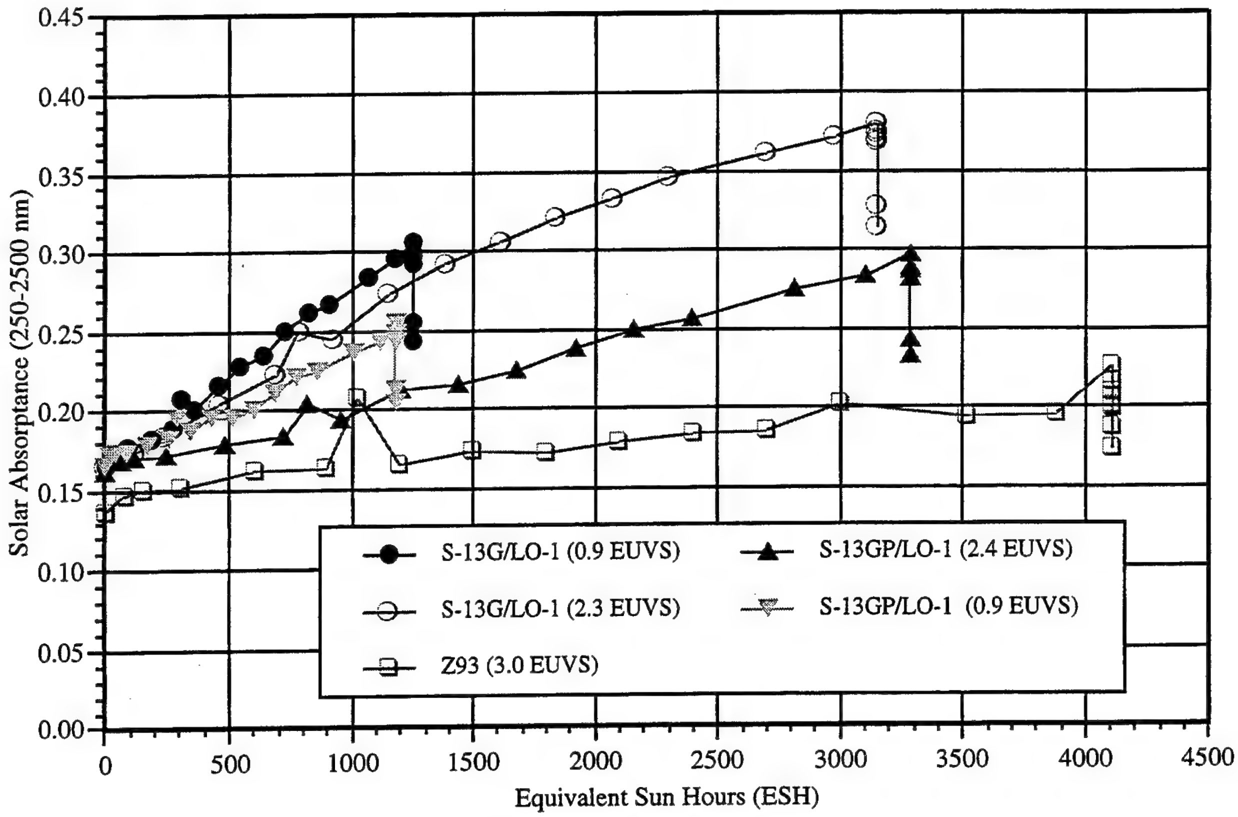

Figure 6. SCEPTRE Test 94QV01 of S-13G/LO-1 & S-13GP/LO-1 Materials.

verify that electron only radiation is more damaging to the material than synergistic UV and electron exposure. Thus, as mentioned earlier, the specimens were exposed to 74 hours of electron only radiation after receiving 1295 hours of synergistic UV and electron radiation. Figure 6 shows (after the ESH values associated with the 1295 hrs. of exposure for each of the specimens) that the electron only exposure of the specimens at the end of the test damaged the materials more severely than the synergistic exposure in the same fashion as had previously been experienced at the 341 hour mark in the test. As before, the damage is most severe in the Z-93 specimen, but this time is not as dramatic (almost imperceptible in some) in the S-13G/LO-1 and S-13GP/LO-1 specimens.

The next step was to try to determine what exactly was the cause of "recovery" of the specimens' reflectance properties. Was it the UV radiation, the increase in thermal energy in the

material, or just "dark time" recovery? Experimentation was conducted to try to determine the cause. First the specimens were allowed to "rest" in the dark for a period of three days and then for a total of eight days. This dark time did allow the S-13G/LO-1 and S-13GP/LO-1 specimens to recover to the same extent that they had after the lamp explosion incident, but the Z-93 specimen did not. The next attempt to determine the cause of the Z-93 recovery was to elevate the specimen temperatures for an eight hour period to see if the added thermal energy resulted in recovery. This did not have a significant effect. At this point it was concluded that the only cause of the Z-93's recovery from the electron only radiation could be the UV radiation and further experimentation was not pursued.

Over the holidays the specimens were allowed an extended period of rest (27 more days had elapsed) before the vacuum chamber was opened and the specimens were visually examined. However, before the chamber was finally opened, the specimens' solar absorptances were measured again. During this time none of the specimens had recovered any further. The chamber was then brought back to ambient conditions and the solar absorptances of each of the specimens was measured again. This time all specimens did exhibit the most significant amount of recovery yet displayed during the experimentation. The specimens were then allowed to set in the chamber at atmospheric pressures for twelve more days and their solar absorptances were measured for the final time before removing the specimens from the chamber.

It is important to note that similar behaviors and ensuing investigations were noted and performed for thermal control coatings in the late 1960s. In 1968 Brown, *et al.*, (ref. 17) reported on reflectance recovery rates for S-13G after exposure to atmospheric conditions for various lengths of time after exposure to electron only radiation. This same report documents UV induced recovery for S-13 and a thermal control material made up of a mix of ZnO and TiO_2 pigments in a mix of silicone and silicate binders (commonly symbolized as ZnO/TiO_2-silicone/silicate) after their exposure to electron only radiation. Another report by this same group (ref. 18) documents in-vacuum, "dark time", reflectance recovery for S-13G, TiO_2/Al_2O_3-potassium silicate, anatase TiO_2-methyl silicone, and rutile TiO_2-methyl silicone after exposure to electron only radiation.

3.3 SCEPTRE 95QV01 Test

The 95QV01 test of the IITRI Z-93P replacement coating was conducted from 30 May 1995 through 7 August 1995, with electron only experimentation lasting for ten more days. The test consisted of 1255 hours of synergistic UV and electron exposure for the specimens with an additional 50 hours of electron only exposure on the specimens at the end of the test. The exposed specimen's optical performance is shown in Figure 7 and Table 1 summarizes both the specimen's optical performance and environment. Execution of the 95QV01 test was also plagued by a lamp explosion. This time the explosion occurred at 690 hours into the test and was discovered only one hour after it occurred. A new lamp was installed and exposure continued six days later. The test was continued with the new lamp until the specimens had received 1255 hours of exposure, when the lamp quit running and the formal test was terminated.

Following the formal test, it was decided to repeat the electron only exposure experimentation conducted in the 94QV01 test. The specimens were exposed to electron only radiation for a period of 50 hours. Figure 7 shows (after the ESH values associated with the 1255 hrs. of exposure for each of the specimens) that the electron only exposure does indeed damage both the Z-93 and Z-93P materials more severely than the synergistic UV and electron exposure. After the specimens were exposed to the electron only radiation they were allowed to rest two days and their optical properties were again measured. The specimens did recover their reflectance a bit, but not significantly (change in solar absorptance ranges from -0.003 to -0.007). The specimens were allowed to rest three more days and their properties were measured before being exposed to atmospheric conditions. After the exposure to atmospheric conditions, their reflectance spectra were measured again. Finally, the specimens were allowed to rest in the chamber (exposed to atmospheric conditions) for 12 more days, after which their reflectance spectra were measured for a final time.

Visual inspection of the specimens revealed that the R-120 batch of the Z-93P specimens had experienced a substantial amount of cracking in the coating that neither the U-151 batch of Z-93P nor any of the Z-93 materials from this or the previous tests exhibited. Additionally, the specimen of Z-93P (batch R-120) which received the most UV radiation (2.5 EUVS) exhibited a bit more cracking than did the one that received the 2.1 EUVS.

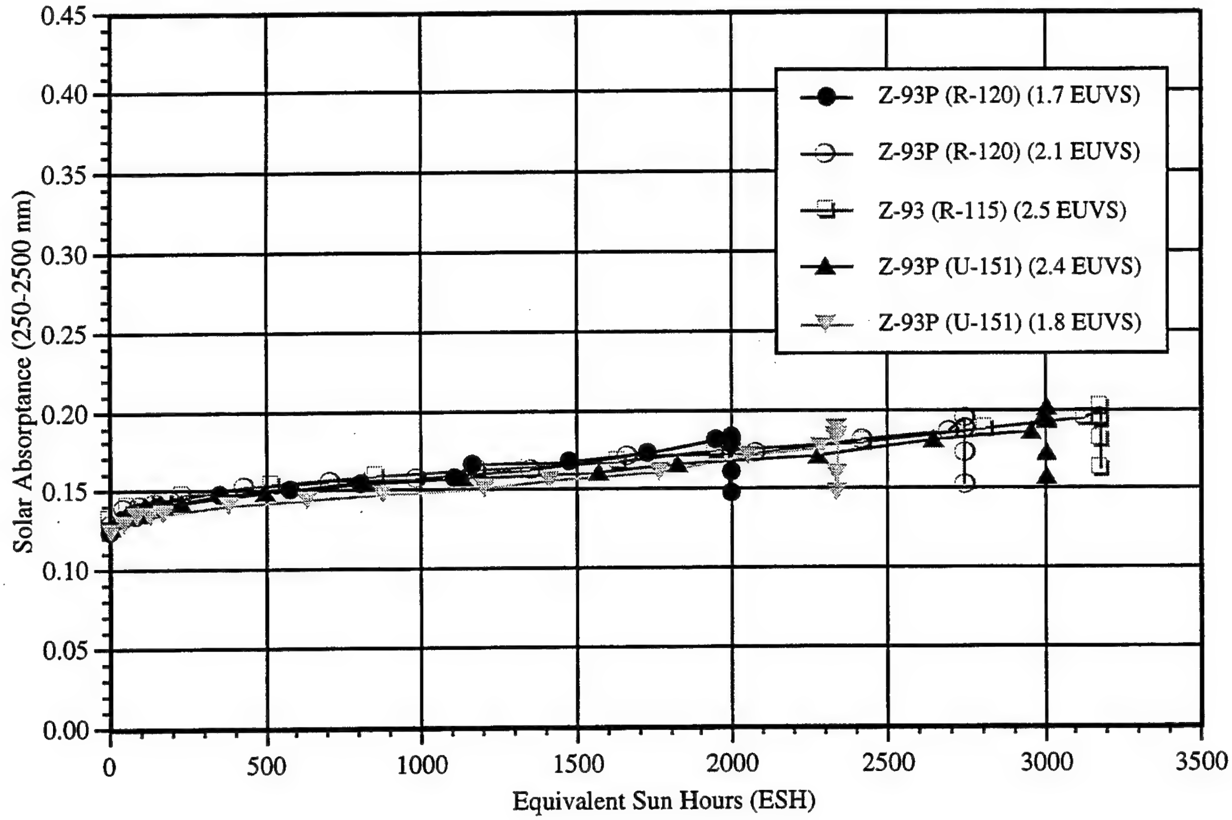

Figure 7. SCEPTRE Test 95QV01 of Z-93 & Z-93P Materials.

3.4 Similar Testing at the Aerospace Corporation

Simulated space environment testing was also performed on old and new formulations of S-13G/LO-1, Z-93, and YB-71 coatings at The Aerospace Corporation in El Segundo, California (ref. 5). The facilities at Wright Laboratory Materials Directorate and that at The Aerospace Corp. are similar, however the primary difference in them is that the SCEPTRE Facility has the ability to perform *in situ* reflectance measurements while the Aerospace facilities do not. On the other hand, The Aerospace Corp. has the ability to expose their test specimens to higher electron energies (up to 120 KeV) and have a greater ability to restrict the specimen temperatures to below 35°C by water filtering the solar simulation and better active cooling of the specimens

which the SCEPTRE facility does not have. Testing at The Aerospace Corp. consisted of three different tests of the IITRI materials: Paint Test #1, the ZOT Test, and Paint Test #2.

Paint Test #1 was designed to reproduce the testing performed in the SCEPTRE Facility's 93QV01 test of the YB-71 and YB-71P materials by mimicking the UV and electron radiation exposures used at the SCEPTRE Facility during that test. The other two tests (the ZOT test and Paint Test #2) consisted of similar UV and electron exposure rates but only a single electron energy level of 40 KeV. Table 3 shows the changes in solar absorptance for all IITRI specimens exposed in both the USAF WL/ML SCEPTRE Facility and The Aerospace Corporation. This table groups the data according to material type and IITRI batch number. In comparing results from the two facilities it was decided to report the changes in solar absorptance from the SCEPTRE Facility as measured in air prior to any vacuum or radiation exposure and after exposure to air at the conclusion of all testing, including any additional electron only experimentation. The Aerospace changes in solar absorptance are the difference between the pretest measurements (in air) and the post-test measurements made in air immediately following gaseous nitrogen purging.

The change in solar absorptance of the Z-93 in the SCEPTRE tests ranged from 0.040 to 0.062 compared to the variation in change in solar absorption in the Aerospace tests from 0.025 to 0.089. The change in solar absorptance for both batches of the Z-93P material in the SCEPTRE tests was 0.048 and in the Aerospace tests it varied from 0.013-0.068. The change in solar absorptance for S-13G/LO-1 in the SCEPTRE test was 0.206 and in the Aerospace tests the change varied from 0.059-0.131. The change in solar absorptance for S-13GP/LO-1 in the SCEPTRE test was 0.122 and in the Aerospace tests the change varied from 0.058-0.341.

Throughout all tests (both WL's and Aerospace's) the Z-93 and Z-93P materials performed similarly. The R120 batch of Z-93P material exhibited cracking from exposure in both facilities that the other Z-93 and Z-93P batches did not.

The S-13G/LO-1 material did not perform similarly in the two facilities. Its performance in the SCEPTRE 94QV01 Test was the worst of all three tests (94QV01, Paint Test #1, and Paint Test #2) and its performance in the duplicate Aerospace Corp. Paint Test #1 was best of the three

(change in solar absorptance in Paint Test #1 was 0.059 versus 0.206 in 94QV01). It is interesting that the performance in identical tests of the same batch of material with specimens

TABLE 3

COMPARISON OF USAF WL AND THE AEROSPACE CORPORATION DATA FOR IITRI MATERIALS

Test	Batch	Specimen Number(s)	EUVS (250-400 nm)	1 KeV fluence (e-/cm2)	10 KeV fluence (e-/cm2)	40 KeV fluence (e-/cm2)	Change in solar absorptance (in air)
S-13G/LO-1							
USAF WL 94QV01 (1295 hrs.)*	Q090	MM-1 & MM-3	0.9 & 2.3	3.0E+16	1.5E+16		0.088 & 0.161
TAC Paint Test 1 (1150 hrs.)	Q090	MM-2	2.0	1.7E+16	8.5E+15		0.059
TAC Paint Test 2 (1226 hrs.)	S174	X-36,-37, &-38	2.1			3.0E+16	0.126, 0.121, & 0.116
TAC Paint Test 2 (1226 hrs.)	T114	CH-1, CH-2, & CH-4	2.1			3.0E+16	0.131, 0.124, & 0.108
S-13GP/LO-1							
USAF WL 94QV01 (1295 hrs.)*	R055	MM-75 & MM-76	2.4 & 0.9	3.0E+16	1.5E+16		0.080 & 0.046
TAC Paint Test 1 (1150 hrs.)	R055	MM-84 & MM-85	2.0	1.7E+16	8.5E+15		0.082 & 0.058
TAC Paint Test 2 (1226 hrs.)	R055	MM-77, MM-81, MM-86, & #0	2.1			3.0E+16	0.341, 0.285, 0.316, & 0.260
TAC Paint Test 2 (1226 hrs.)	S174	Y-37, Y-38, & Y-39	2.1			3.0E+16	0.141, 0.112, & 0.136
YB-71							
TAC ZOT Test (1233 hrs.)	P062	#2	2.1			3.1E+16	0.108
TAC ZOT Test (1233 hrs.)	Q051	#1 & #2	2.1			3.1E+16	0.096 & 0.095
USAF WL 93QV01 (1000 hrs.)	R026	MM-15 & MM-16	2.6 & 1.7	1.7E+16	8.3E+15		0.143 & 0.129
TAC Paint Test 1 (1150 hrs.)	R026	#01	2.0	1.7E+16	8.5E+15		0.077
TAC ZOT Test (1233 hrs.)	R026	#2 & #3	2.1			3.1E+16	0.175 & 0.194
USAF WL 93QV02 (1265 hrs.)	R123	C-017	2.8	2.0E+16	1.0E+16		0.185
TAC Paint Test 1 (1150 hrs.)	R123	C015 & C016	2.0	1.7E+16	8.5E+15		0.045 & 0.039
TAC ZOT Test (1233 hrs.)	R123	C001 & C014	2.1			3.1E+16	0.129 & 0.145
YB-71P							
TAC Paint Test 1 (1150 hrs.)	R028	#02 & #11	2.0	1.7E+16	8.5E+15		0.122 & 0.120
TAC ZOT Test (1233 hrs.)	R028	#5 & #6	2.1			3.1E+16	0.275 & 0.269
USAF WL 93QV01 (1000 hrs.)	R028	IITRI-40 & IITRI-42	2.9 & 2.1	1.7E+16	8.3E+15		0.268 & 0.190
USAF WL 93QV02 (1265 hrs.)	R028	IITRI-45	2.7	2.0E+16	1.0E+16		0.302
USAF WL 93QV02 (1265 hrs.)	S038	X-5 & X-6	2.5 & 1.1(est.)	2.0E+16	1.0E+16		0.163 & 0.127
TAC Paint Test 1 (1150 hrs.)	S038	X-2	2.0	1.7E+16	8.5E+15		0.077
TAC ZOT Test (1233 hrs.)	S038	X-7, X-8, & X-9	2.1			3.1E+16	0.207, 0.221, & 0.211
TAC ZOT Test (1233 hrs.)	S081	A-12 & A-18	2.1			3.1E+16	0.323 & 0.305
TAC ZOT Test (1233 hrs.)	T081	B098 & B099	2.1			3.1E+16	0.238 & 0.235
TAC Paint Test 2 (1226 hrs.)	T081	B-97	2.1			3.0E+16	0.238
Z-93							
TAC ZOT Test (1233 hrs.)	G028	#2 & #3	2.1			3.1E+16	0.053 & 0.089
TAC Paint Test 2 (1226 hrs.)	G028	#61 & #62	2.1			3.0E+16	0.036 & 0.034
USAF WL 93QV01 (1000 hrs.)	R009	MM-10	3.2	1.7E+16	8.3E+15		0.053
USAF WL 93QV02 (1265 hrs.)	R009	MM-11	1.2 (est.)	2.0E+16	1.0E+16		0.042
USAF WL 94QV01 (1295 hrs.)*	R009	MM-12	3.0	3.0E+16	1.5E+16		0.049
TAC Paint Test 1 (1150 hrs.)	R009	#05 & #12	2.0	1.7E+16	8.5E+15		0.025 & 0.025
USAF WL 95QV01 (1255 hrs.)*	R115	A-019	2.5	2.9E+16	1.4E+16		0.047
TAC Paint Test 2 (1226 hrs.)	R115	A-002 & A-046	2.1			3.0E+16	0.036 & 0.035
TAC Paint Test 2 (1226 hrs.)	S044	X-32 & X-39	2.1			3.0E+16	0.047 & 0.033
Z-93P							
TAC Paint Test 1 (1150 hrs.)	R016	#06	2.0	1.7E+16	8.5E+15		0.032
TAC Paint Test 2 (1226 hrs.)	R016	#R	2.1			3.0E+16	0.065
USAF WL 95QV01 (1255 hrs.)*	R120	A-117 & A-118	1.7 & 2.1	2.9E+16	1.4E+16		0.042 & 0.045
TAC Paint Test 2 (1226 hrs.)	R120	A-094 & A-110	2.1			3.0E+16	0.023 & 0.032
TAC Paint Test 1 (1150 hrs.)	S044	X-17 & X-18	2.0	1.7E+16	8.5E+15		0.013 & 0.035
TAC Paint Test 2 (1226 hrs.)	S044	X-12, X-15, & X-22	2.1			3.0E+16	0.068, 0.039, & 0.031
USAF WL 95QV01 (1255 hrs.)*	U151	FR-19 & FR-20	2.4 & 1.8	2.9E+16	1.4E+16		0.041 & 0.032

*Reflectance measurements made without gaseous nitrogen purge prior to exposure to atmosphere.

MM-2 and IITRI specimen no. MM-1 (which were right next to each other when they were sprayed) were so different. The S-13GP/LO-1 material's performance was more similar in the duplicate tests. Its change in solar absorptance was 0.122 in the 94QV01 test and 0.058-0.082 in Aerospace's Paint Test #1. The real change occurs in the material's performance when it is exposed to the higher energy electrons used in Aerospace's Paint Test #2. Under these circumstances, the S-13GP/LO-1 material overall performed well, but the particular batch, R-055, used in both the 94QV01 test and Aerospace's Paint Test #1, performed abnormally poor (average change in solar absorptance of all specimens of that batch was 0.301) and has a non-uniform appearance with dark streaks and black lines. Dr. Mike Meshishnek, The Aerospace Corporation, suggests that the higher electron energies used in the Paint Test #2 may have caused arcing on the specimens from charging. It is interesting to note that the one specimen of S-13G/LO-1 in the 94QV01 test exhibited the same appearance that the R-055 batch of S-13GP/LO-1 and it too performed more poorly than the other S-13G/LO-1 and/or S-13GP/LO-1 specimens did in the same test.

4. CONCLUSIONS AND RECOMMENDATIONS

The real test of the newly reformulated coatings would be actual space flight exposure testing. Unfortunately, the most recent chance for this testing literally went up in smoke. The failure of the Pegasus rocket, mentioned earlier, resulted in the lost opportunity for a very valuable chance to compare the extensive testing performed at several different facilities to actual on-orbit calorimeter data for these commonly used materials. Fortunately, there is a second SAMMES experiment (referred to as SAMMES II) currently planned to fly in the future that has all three of the new IITRI materials on it and there are attempts being made to rebuild and fly the original SAMMES, as well.

The susceptibility of the Z-93 and Z-93P materials to degradation in reflectance properties due to electron only exposure may be an issue concerning its actual space flight performance, since in some spacecraft designs radiator surfaces are made to be parallel to solar radiation and therefor are exposed primarily to particulate (electron and proton) radiation. Also, this phenomenon may be of interest to coating developers in helping to understand the nature of the damage mechanism experienced by different types of materials. Additionally, the recovery experimentation that accompanied this testing helps to establish the extents of recovery experienced by different materials due to atmospheric exposure or dark time recovery which is important information for those rare occasions when space flight hardware is brought back to earth for investigation.

The evaluation of the reformulated IITRI white thermal control coatings reveals that for the S-13G/LO-1 and Z-93 coatings, their replacements, S-13GP/LO-1 and Z-93P, are very acceptable. However, there were some batch anomalies discovered with both the Z-93P and S-13GP/LO-1 materials. While these batch variations are no where near as severe as those seen with the YB-71P material, it would be prudent for the users to test the performance of each batch of the new materials prior to their use on spaceflight hardware.

5. ACKNOWLEDGMENTS

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APPENDIX A

SUPPLEMENTAL DATA FOR SCEPTRE 93QV01 TEST

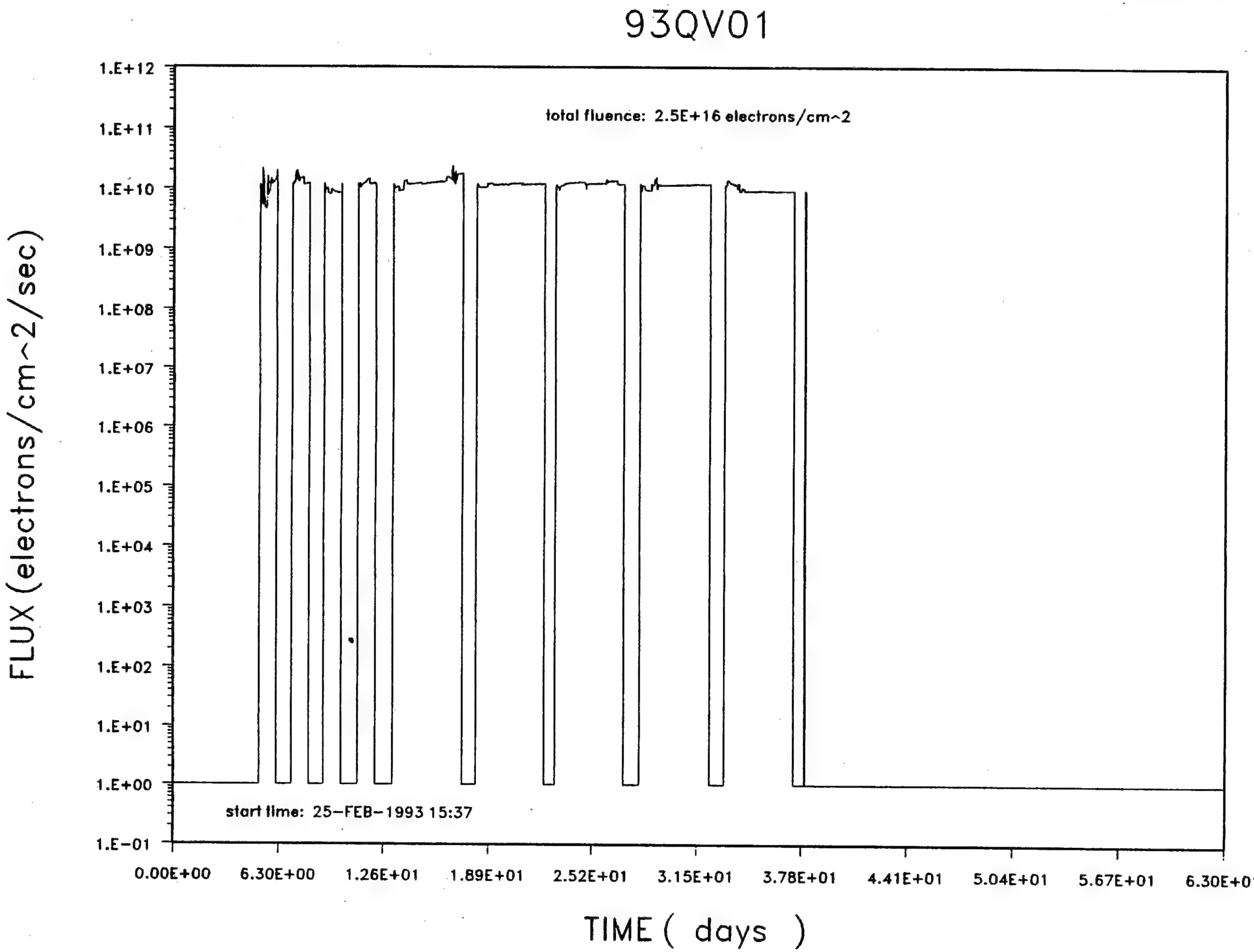

Figure A-1. SCEPTRE Test 93QV01 Electron Flux History.

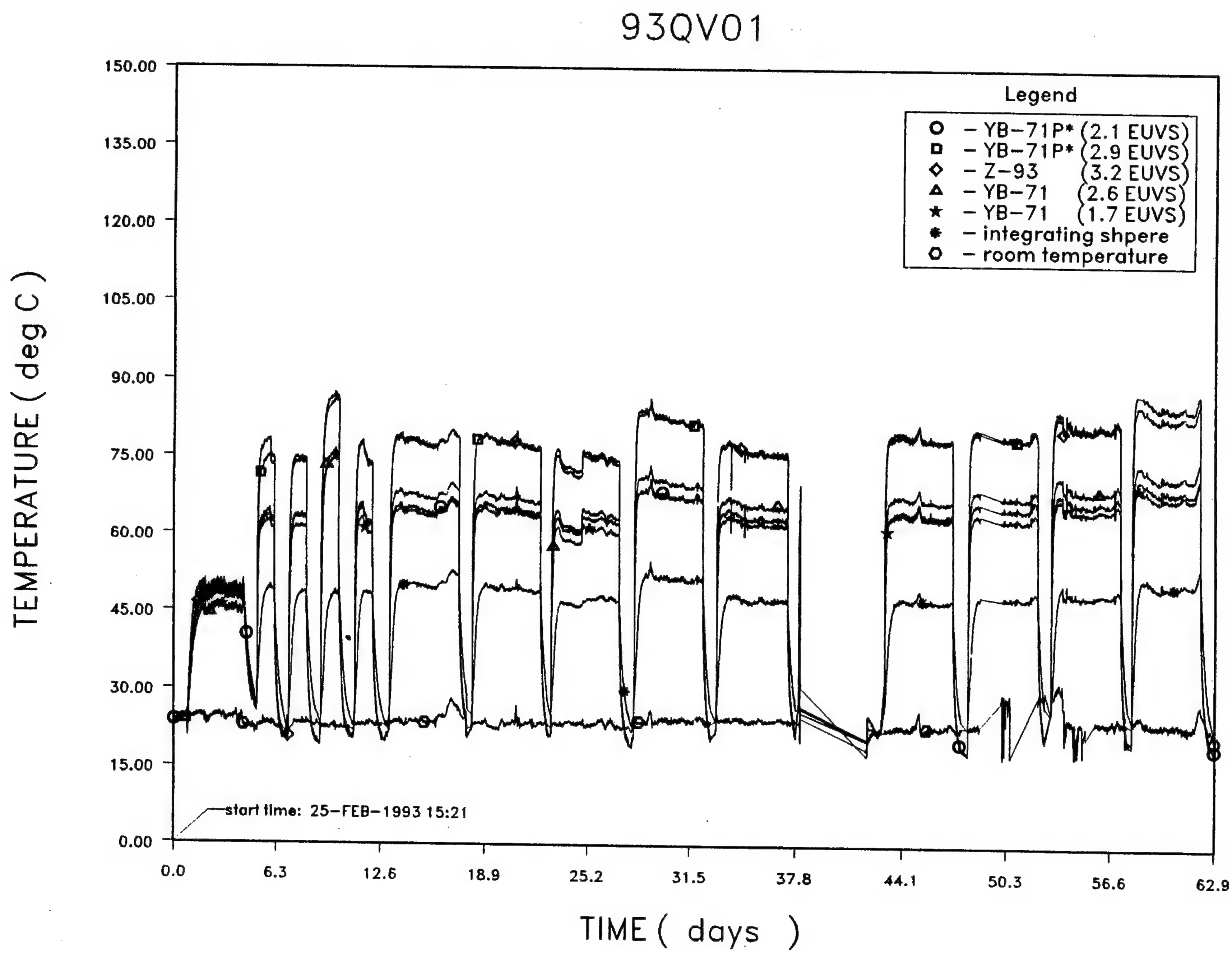

Figure A-2. SCEPTRE Test 93QV01 Specimen Temperature History.

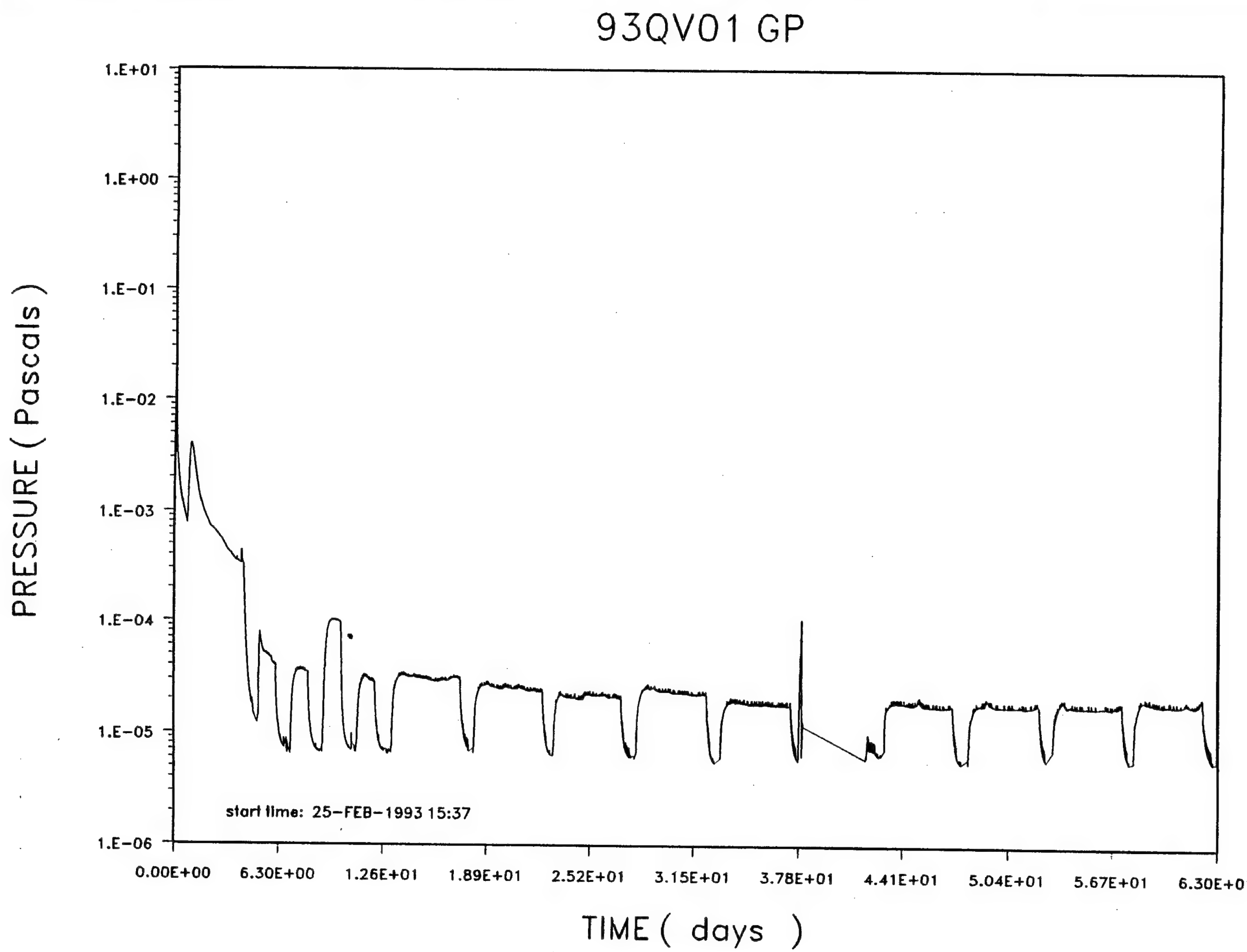

Figure A-3. SCEPTRE Test 93QV01 Granville-Phillips Ion Gauge Vacuum Level History.

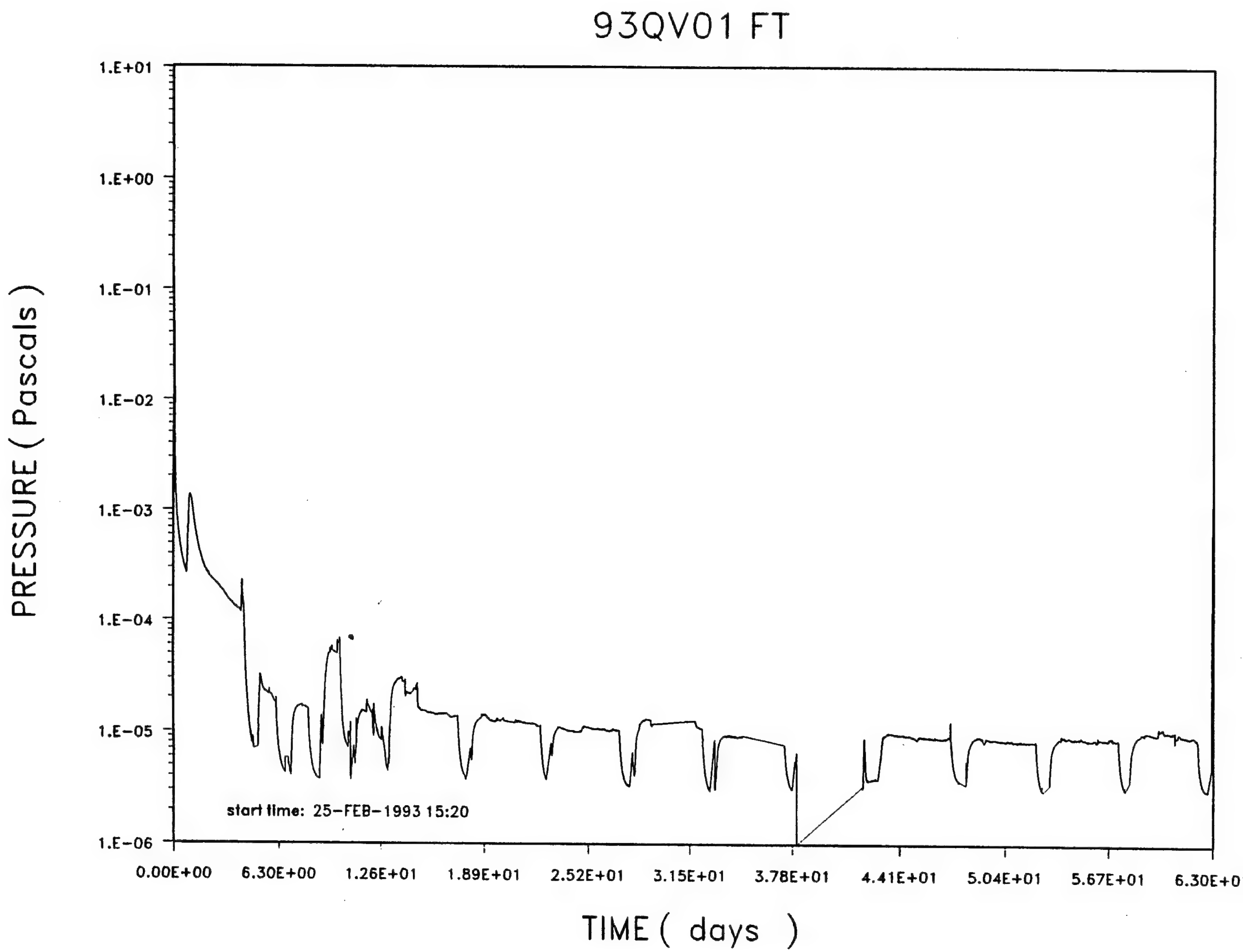

Figure A-4. SCEPTRE Test 93QV01 Fredricks-Televac Ion Gauge Vacuum Level History.

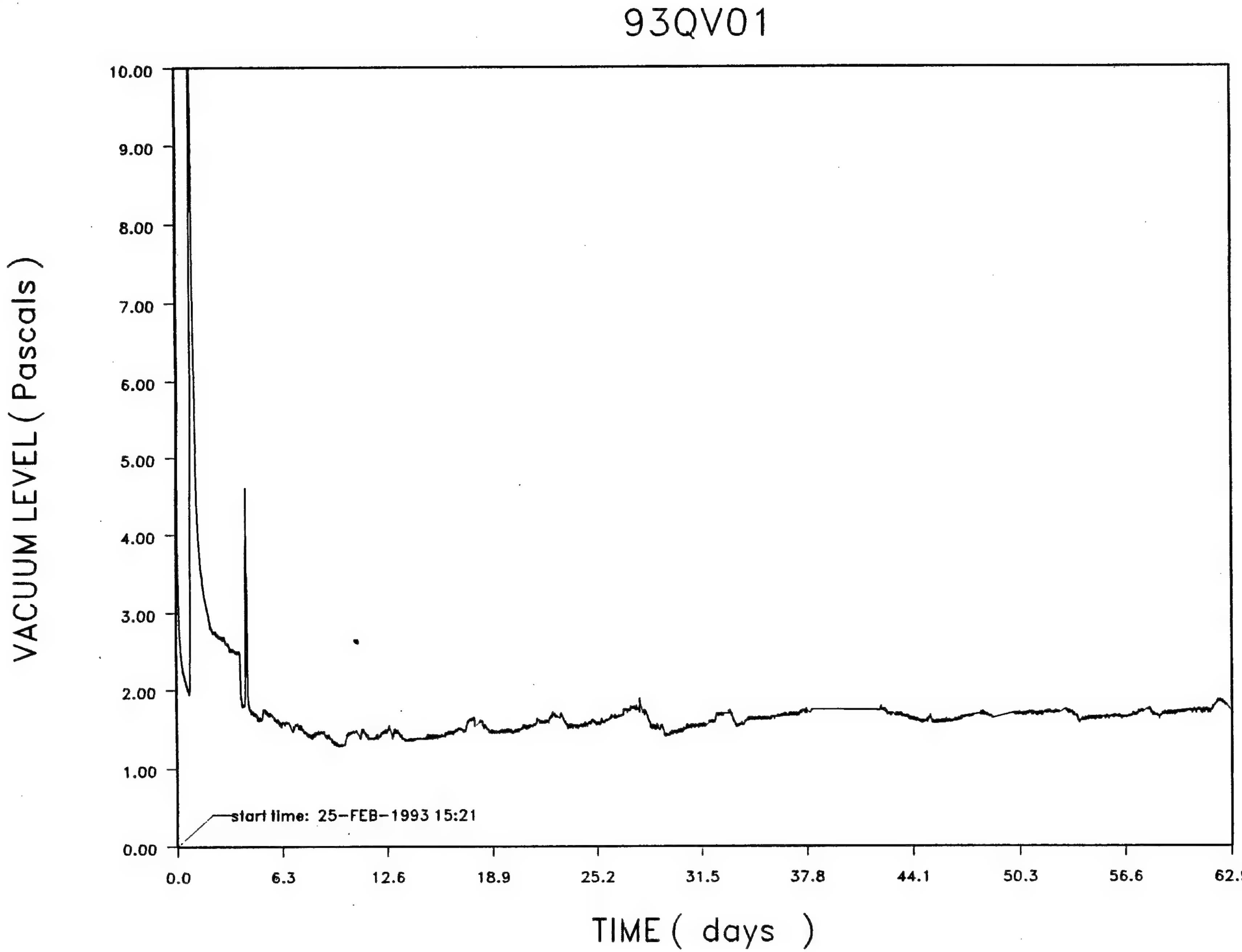

Figure A-5. SCEPTRE Test 93QV01 Foreline Thermocouple Gauge Vacuum Level History.

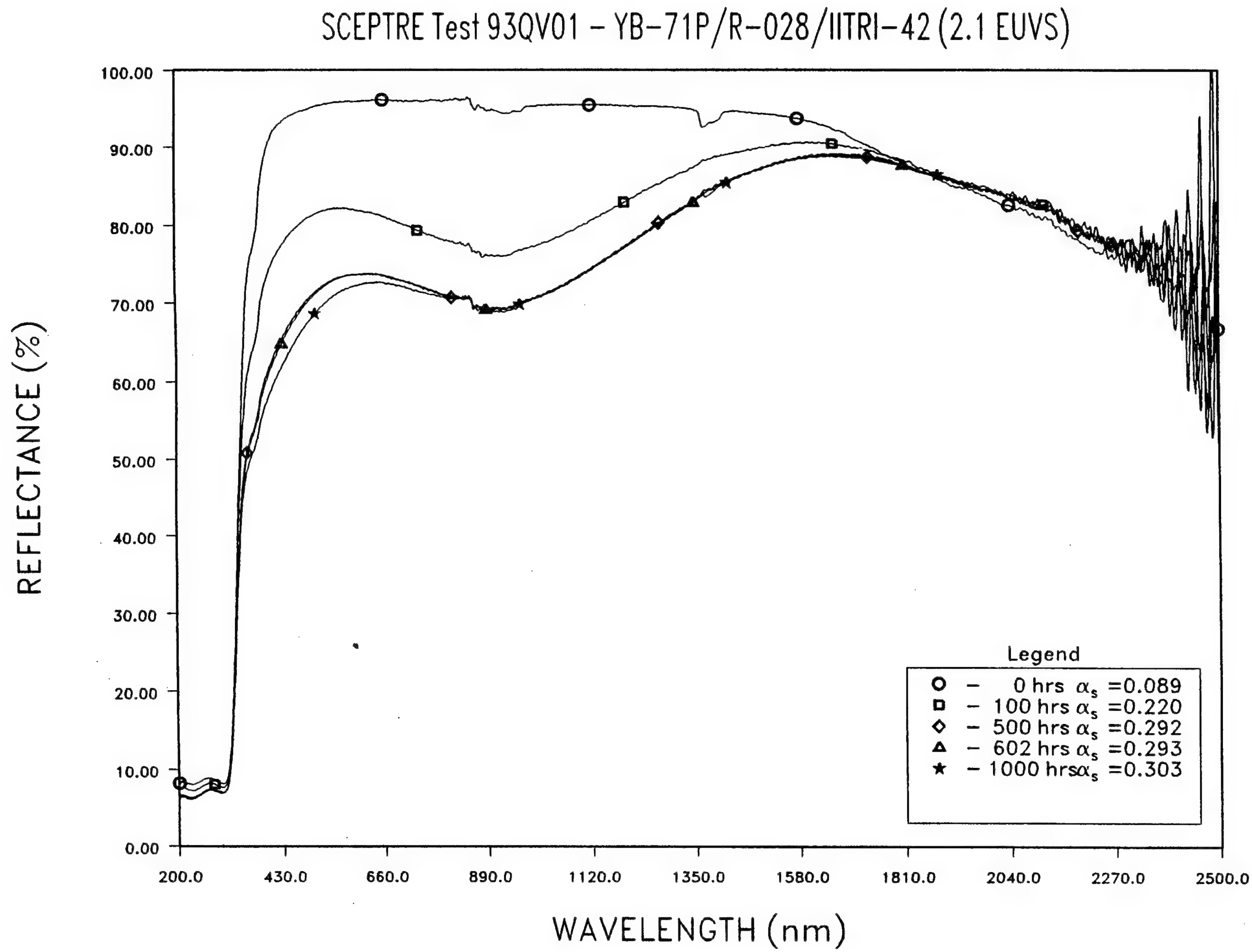

Figure A-6. SCEPTRE Test 93QV01 YB-71P (R-028) (2.1 EUVS) Reflectance Spectra History.

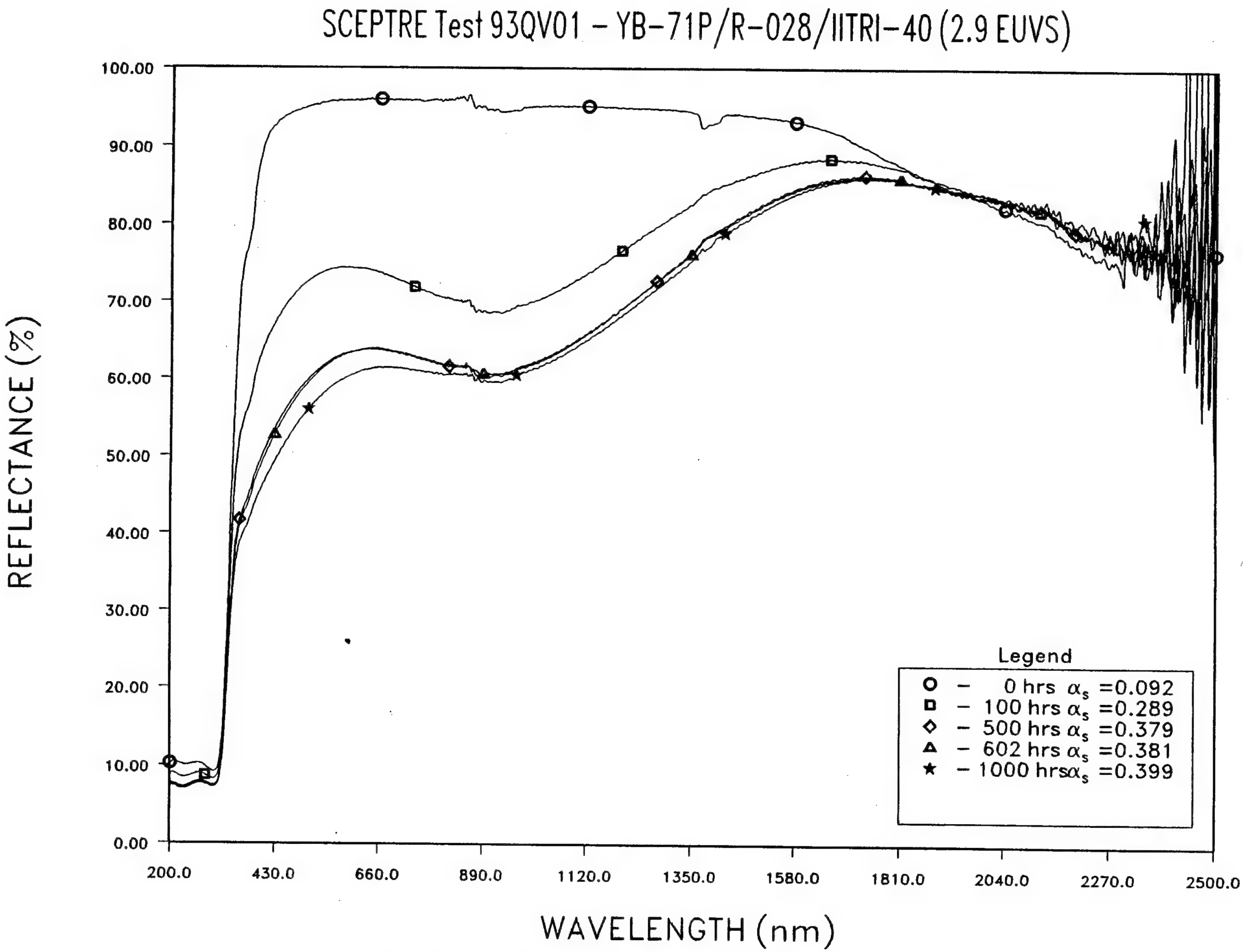

Figure A-7. SCEPTRE Test 93QV01 YB-71P (R-028) (2.9 EUVS) Reflectance Spectra History.

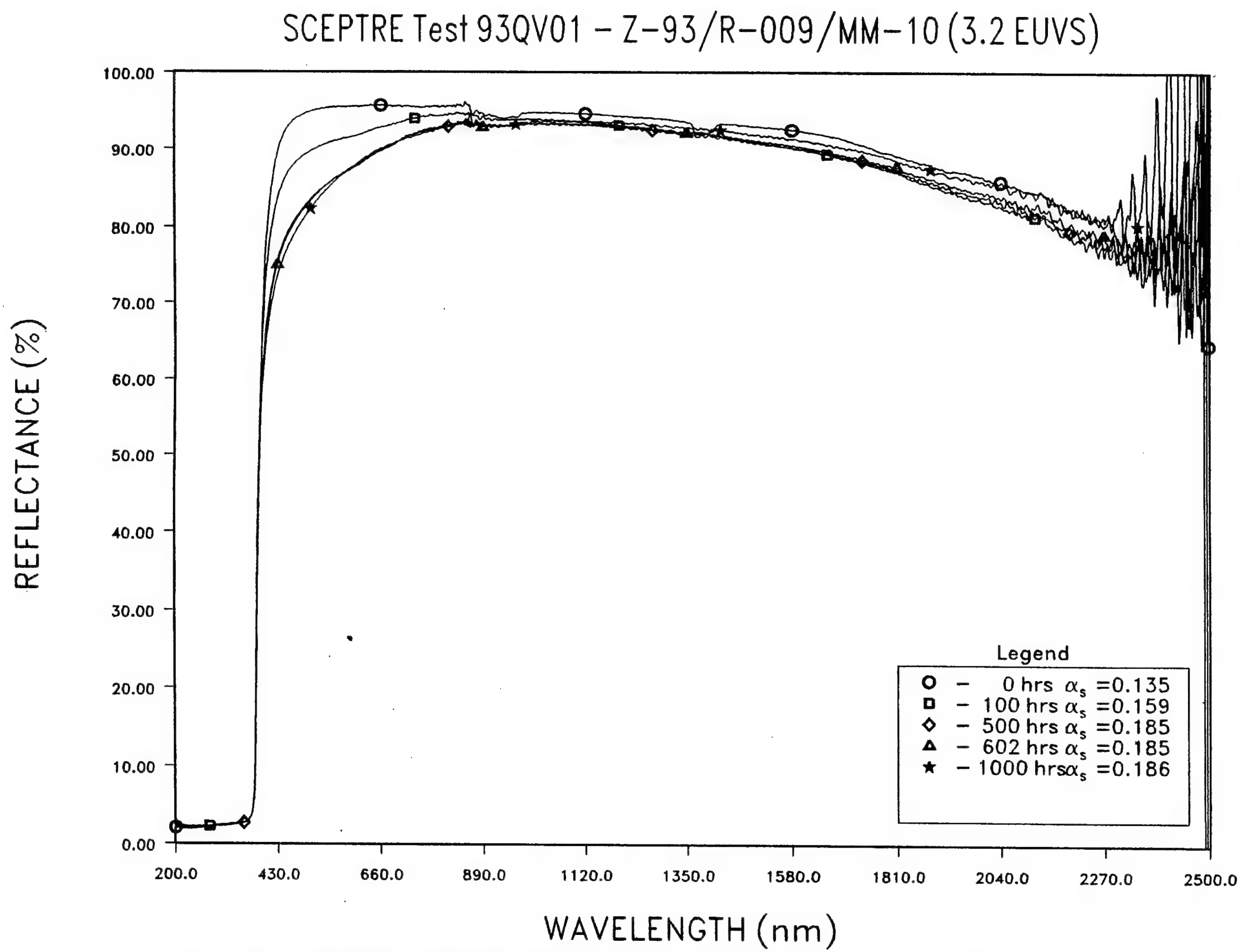

Figure A-8. SCEPTRE Test 93QV01 Z-93 (R-009) (3.2 EUVS) Reflectance Spectra History.

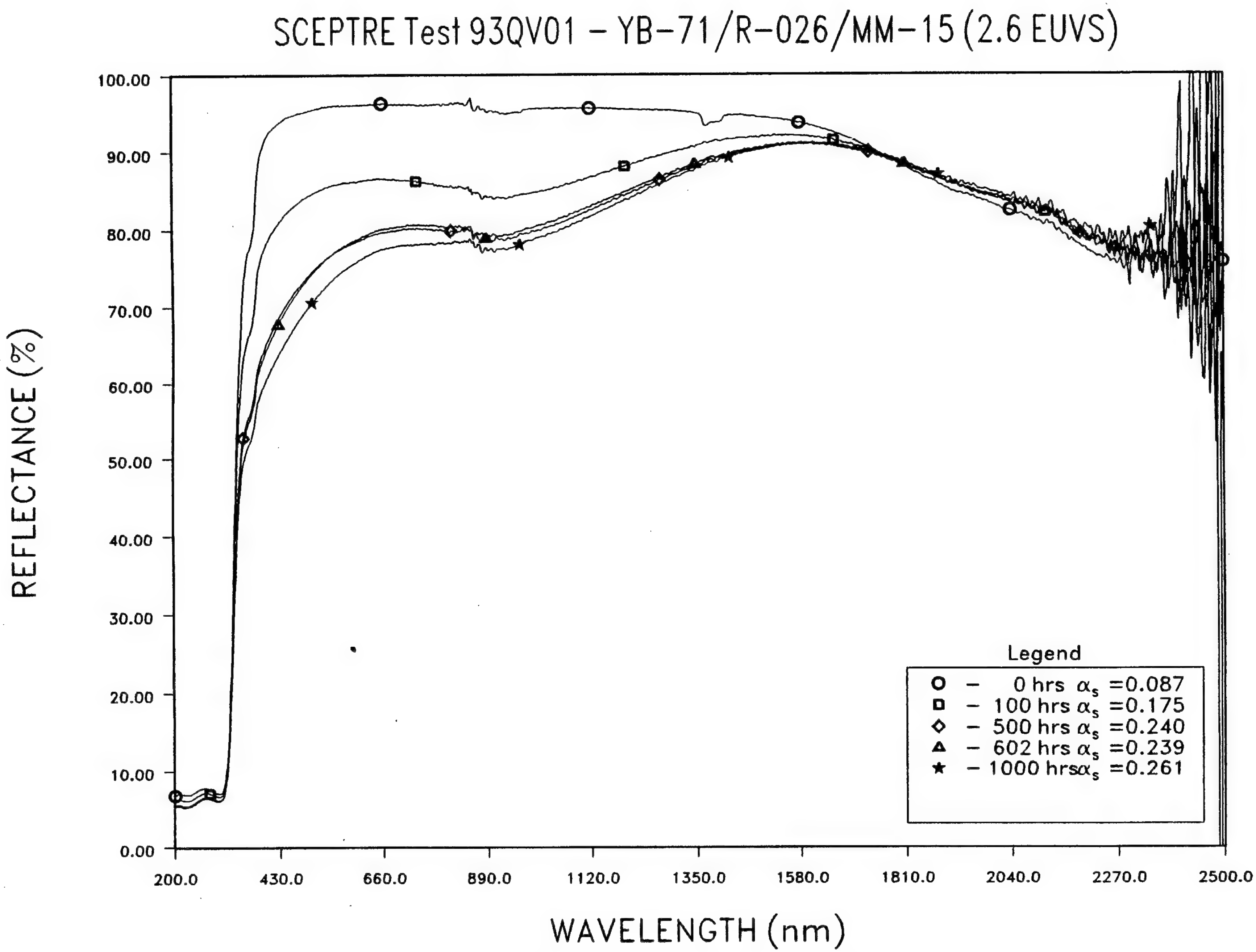

Figure A-9. SCEPTRE Test 93QV01 YB-71 (R-026) (2.6 EUVS) Reflectance Spectra History.

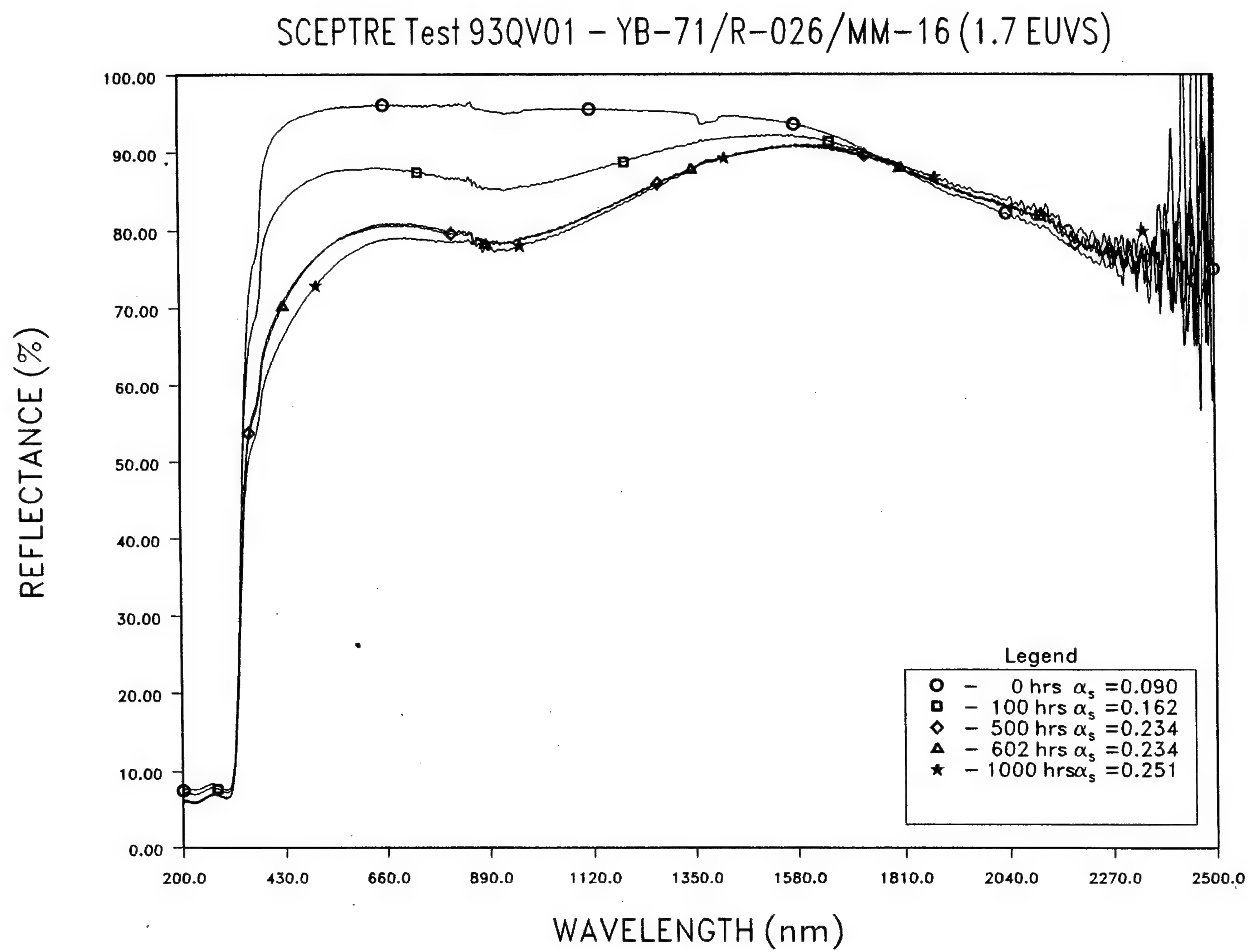

Figure A-10. SCEPTRE Test 93QV01 YB-71 (R-026) (1.7 EUVS) Reflectance Spectra History.

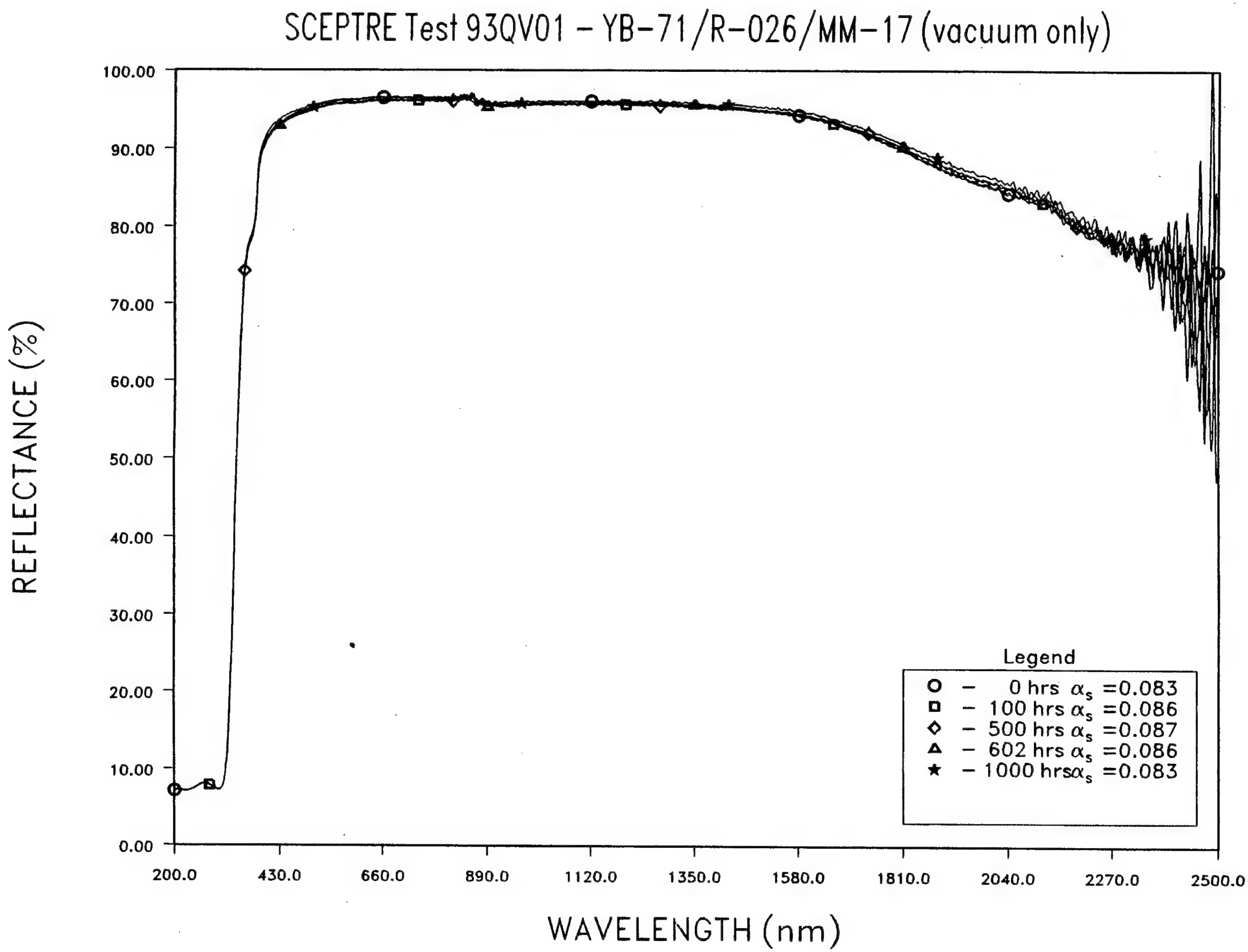

Figure A-11. SCEPTRE Test 93QV01 YB-71 (R-026) (reference) Reflectance Spectra History.

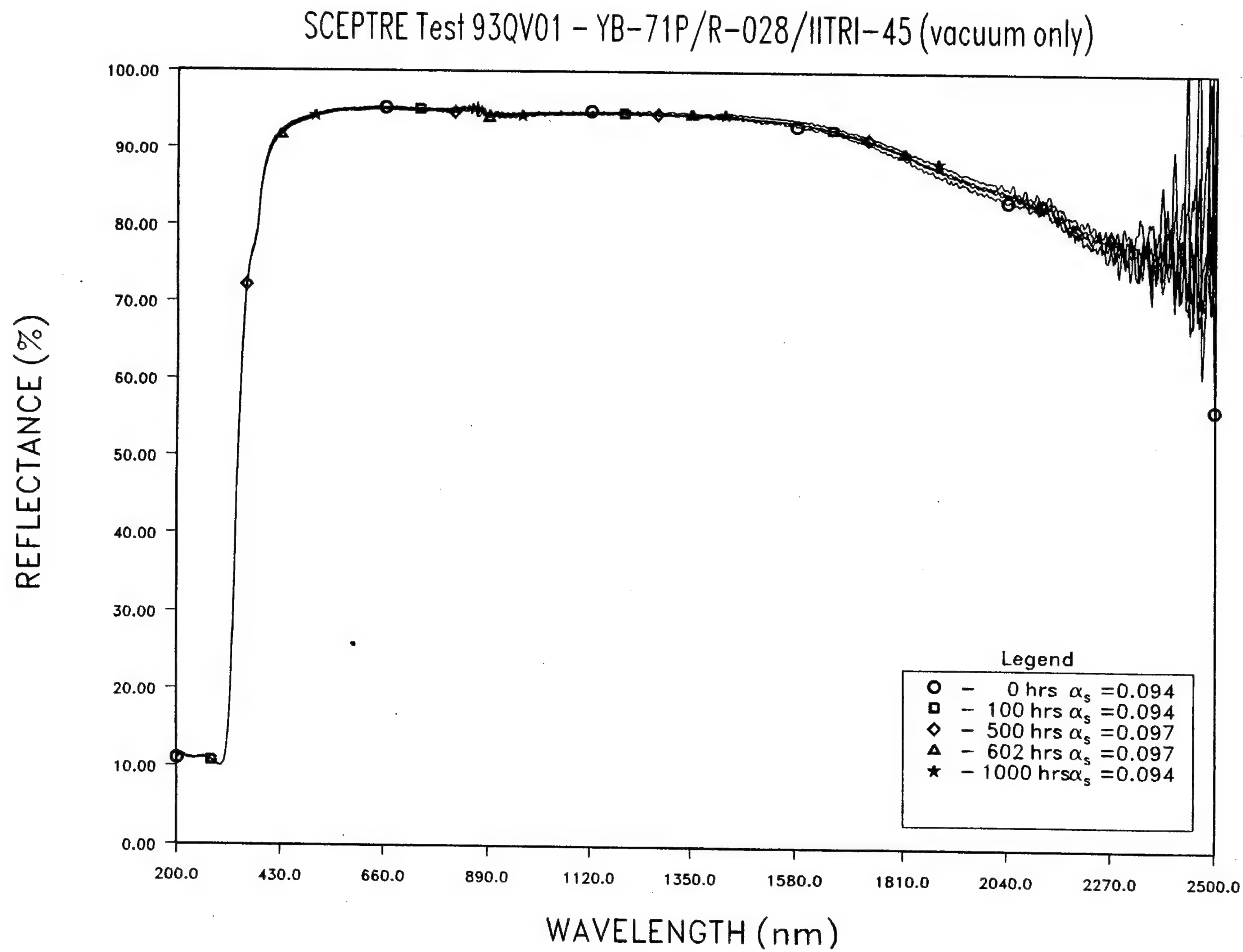

Figure A-12. SCEPTRE Test 93QV01 YB-71P (R-028) (reference) Reflectance Spectra History.

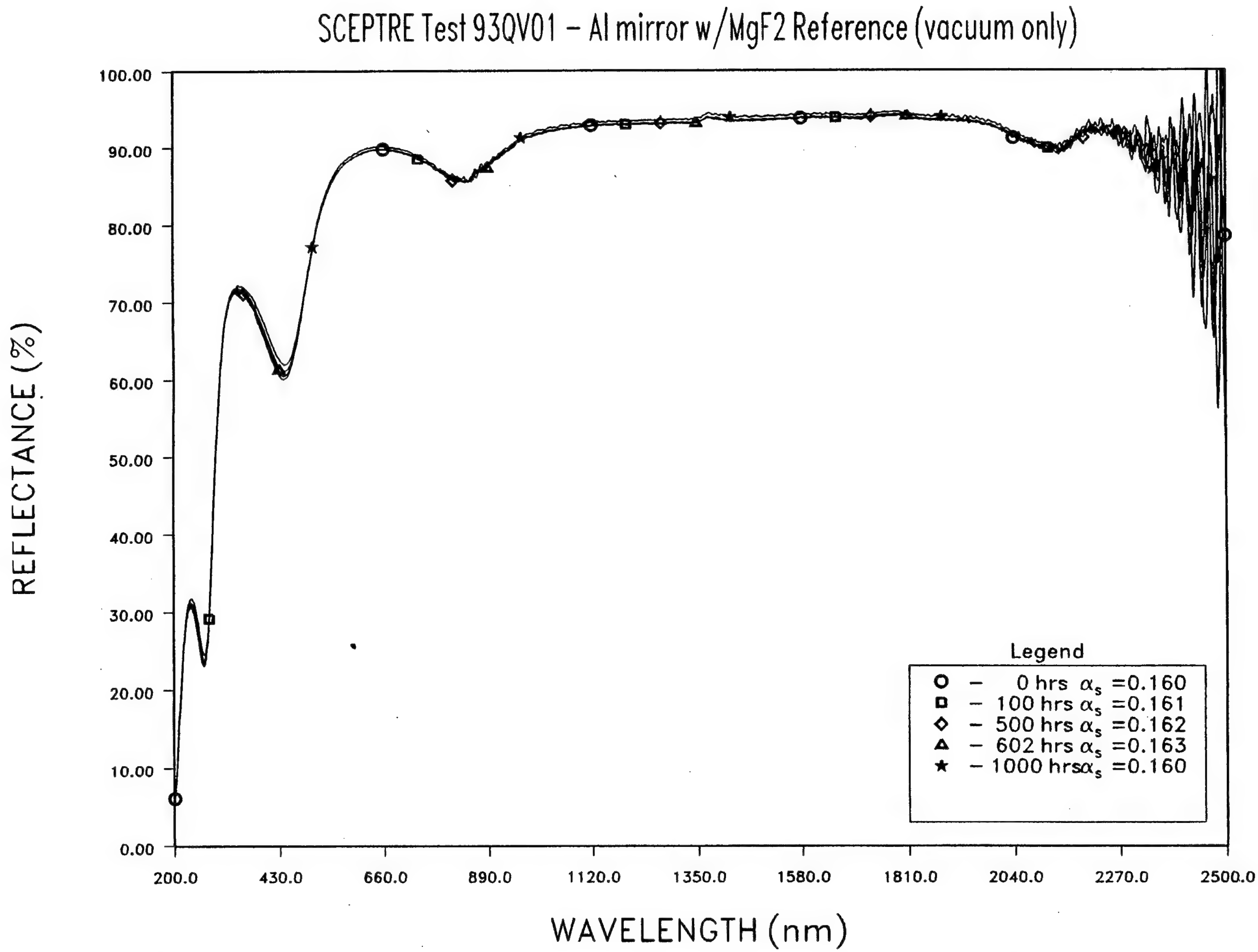

Figure A-13. SCEPTRE Test 93QV01 Al mirror w/MgF_2 (reference) Reflectance Spectra History.

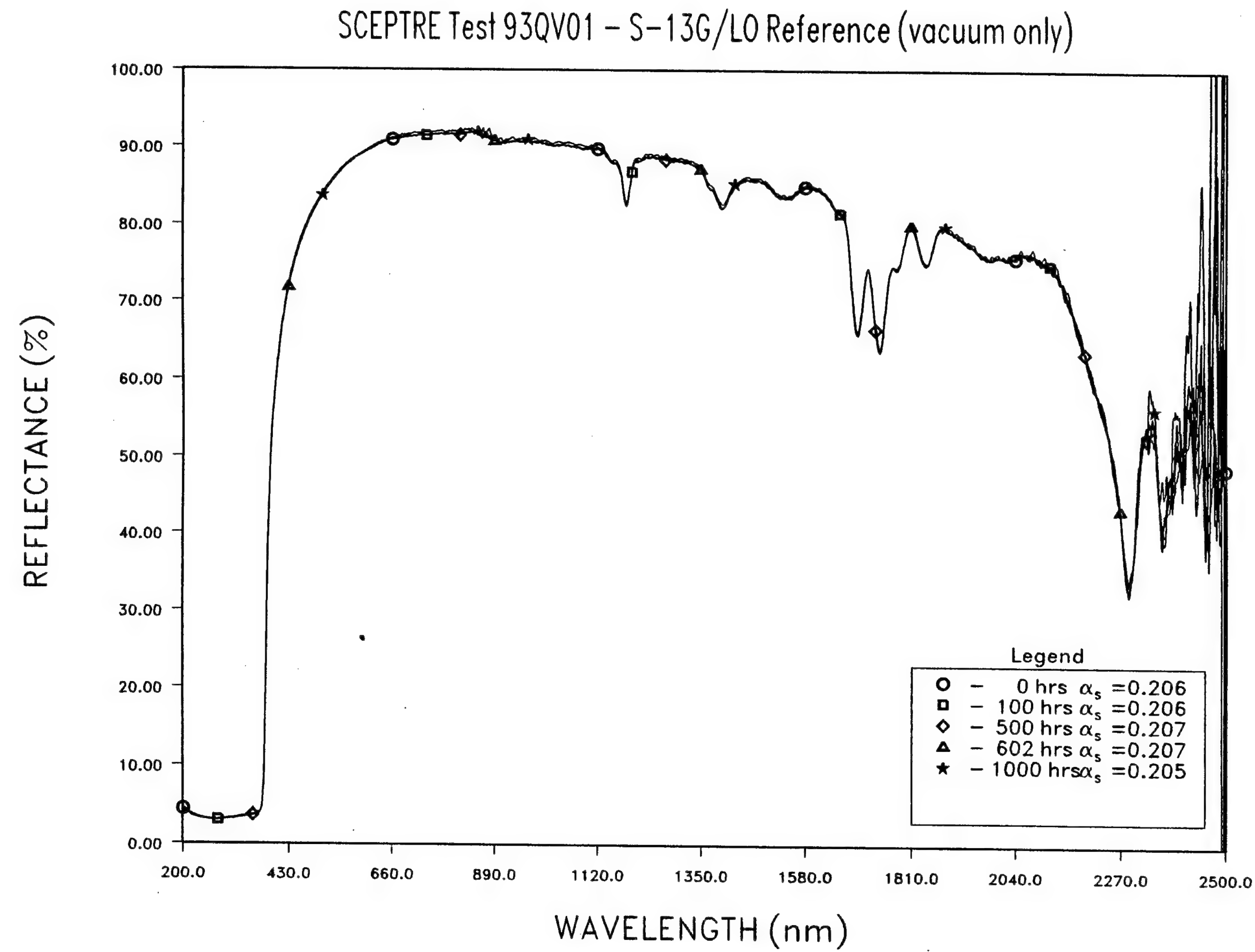

Figure A-14. SCEPTRE Test 93QV01 S-13G/LO (reference) Reflectance Spectra History.

APPENDIX B

SUPPLEMENTAL DATA FOR SCEPTRE 93QV02 TEST

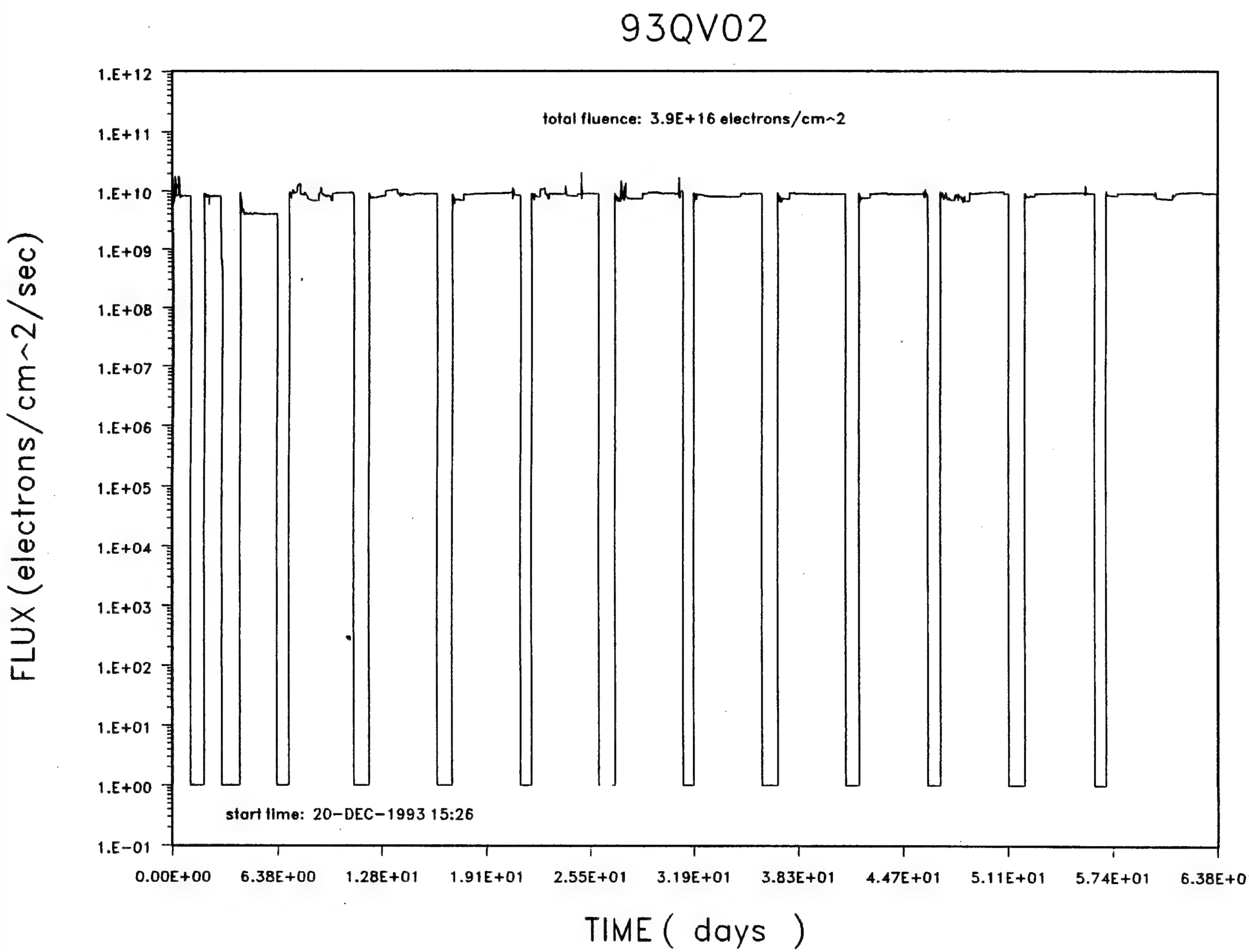

Figure B-1. SCEPTRE Test 93QV02 Electron Flux History.

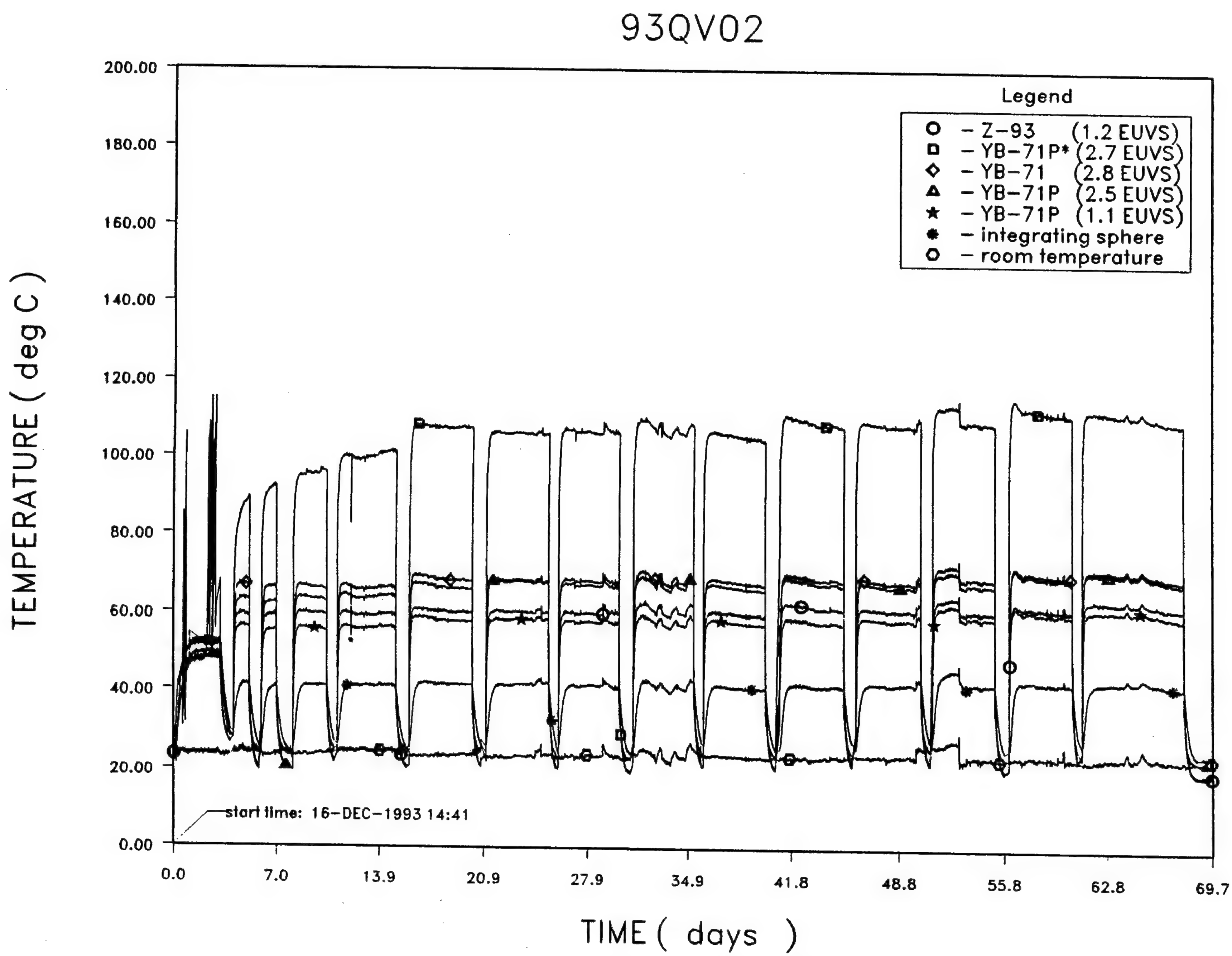

Figure B-2. SCEPTRE Test 93QV02 Specimen Temperature History.

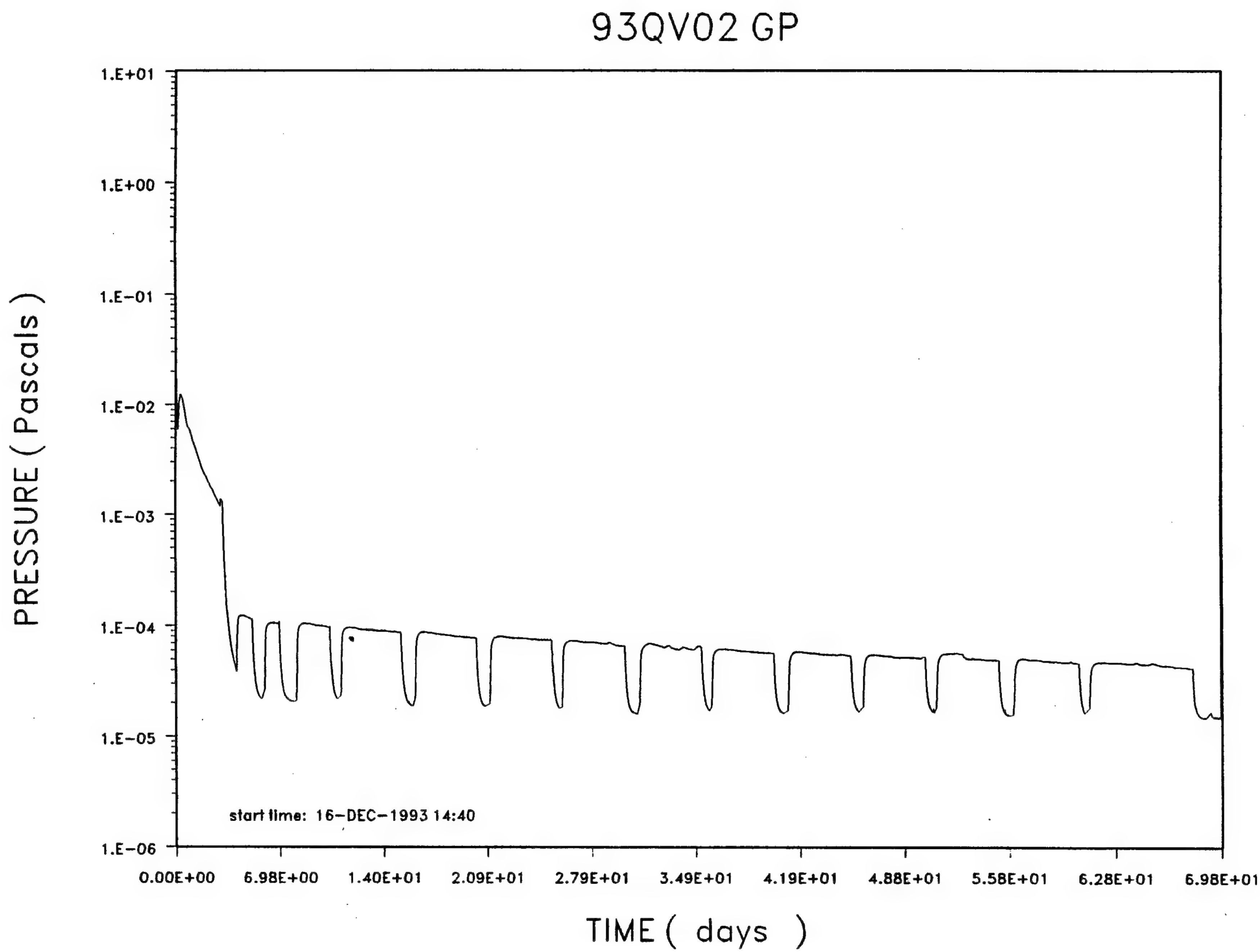

Figure B-3. SCEPTRE Test 93QV02 Granville-Phillips Ion Gauge Vacuum Level History.

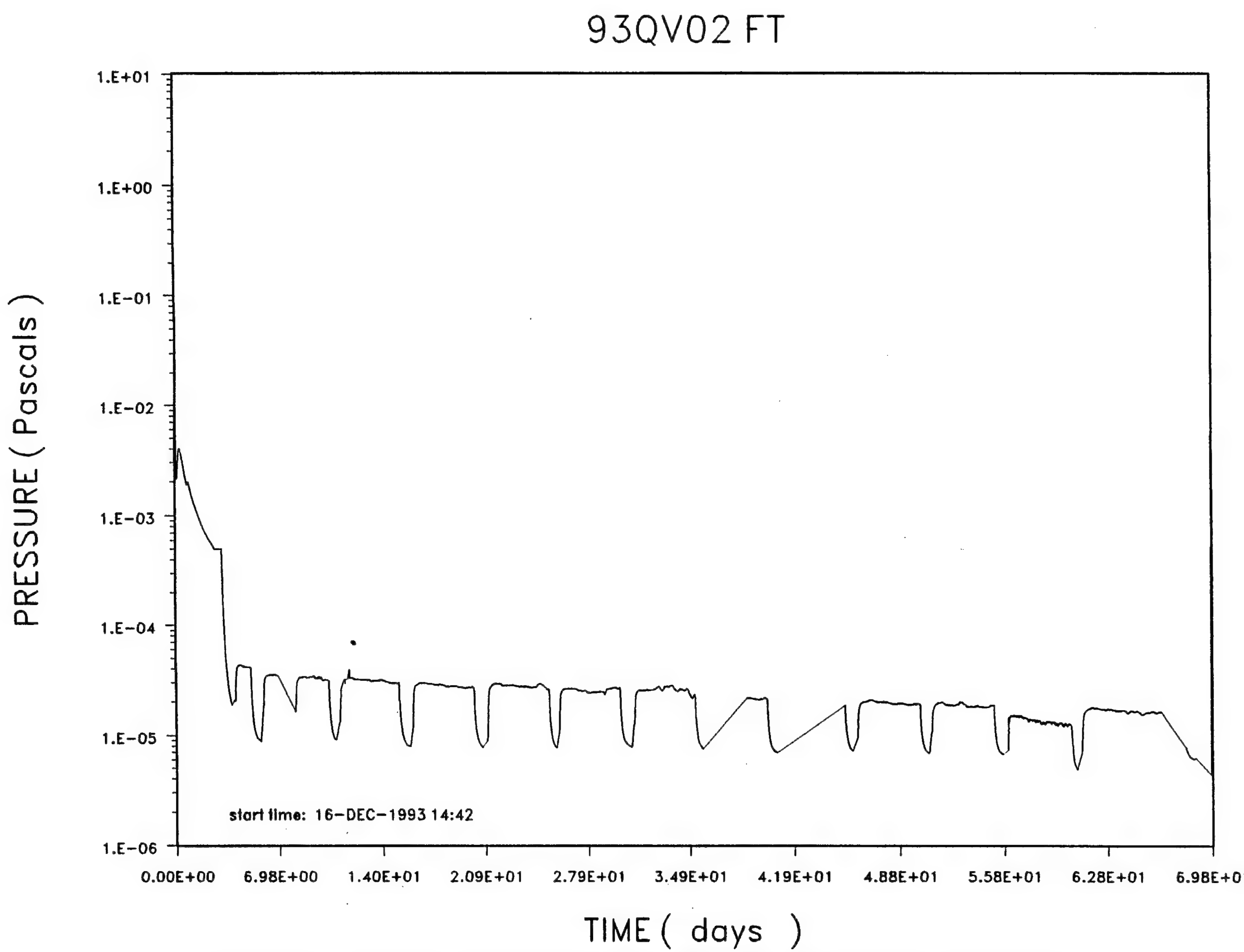

Figure B-4. SCEPTRE Test 93QV02 Fredricks-Televac Ion Gauge Vacuum Level History.

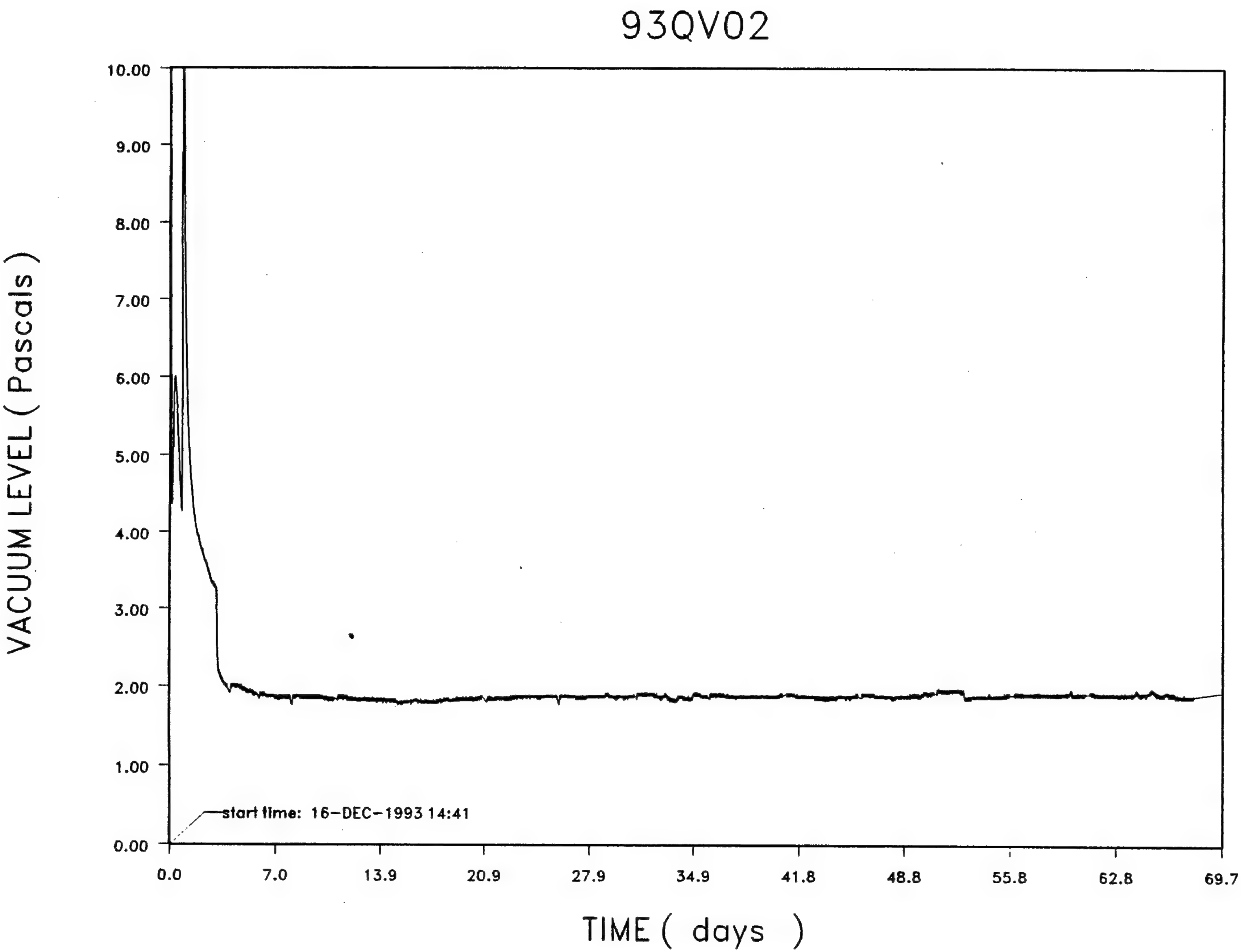

Figure B-5. SCEPTRE Test 93QV02 Foreline Thermocouple Gauge Vacuum Level History.

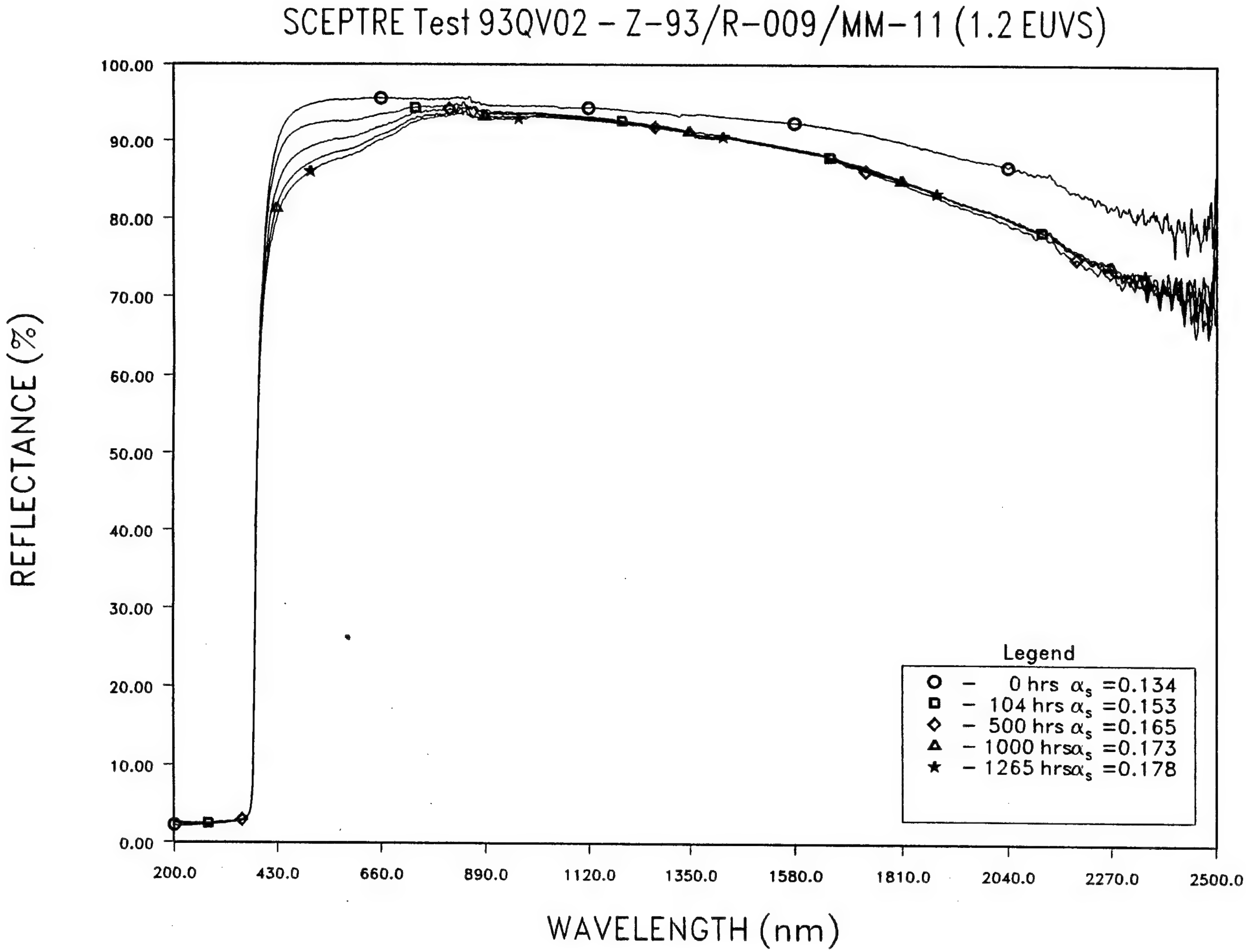

Figure B-6. SCEPTRE Test 93QV02 Z-93 (R-009) (1.2 EUVS) Reflectance Spectra History.

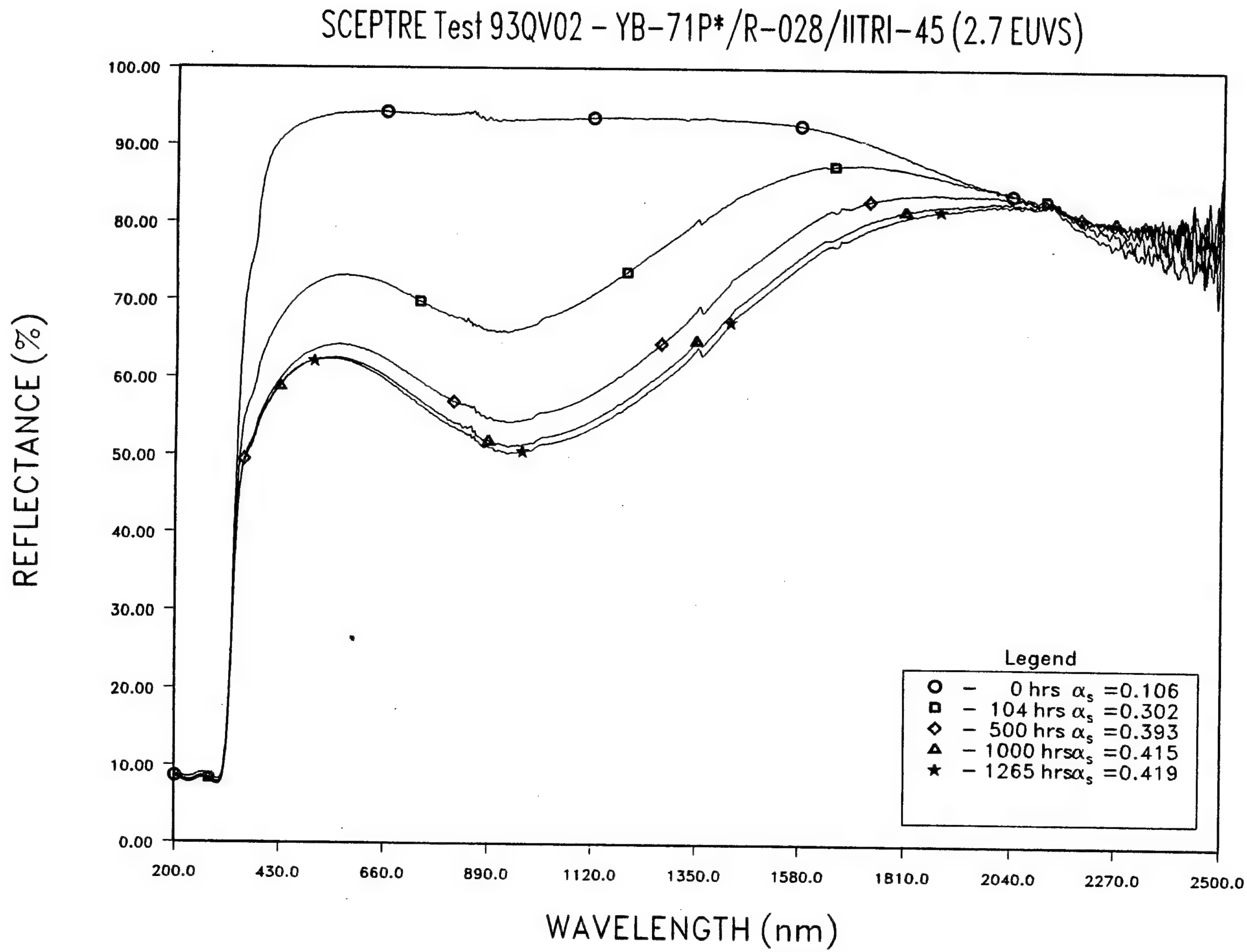

Figure B-7. SCEPTRE Test 93QV02 YB-71P* (R-028) (2.7 EUVS) Reflectance Spectra History.

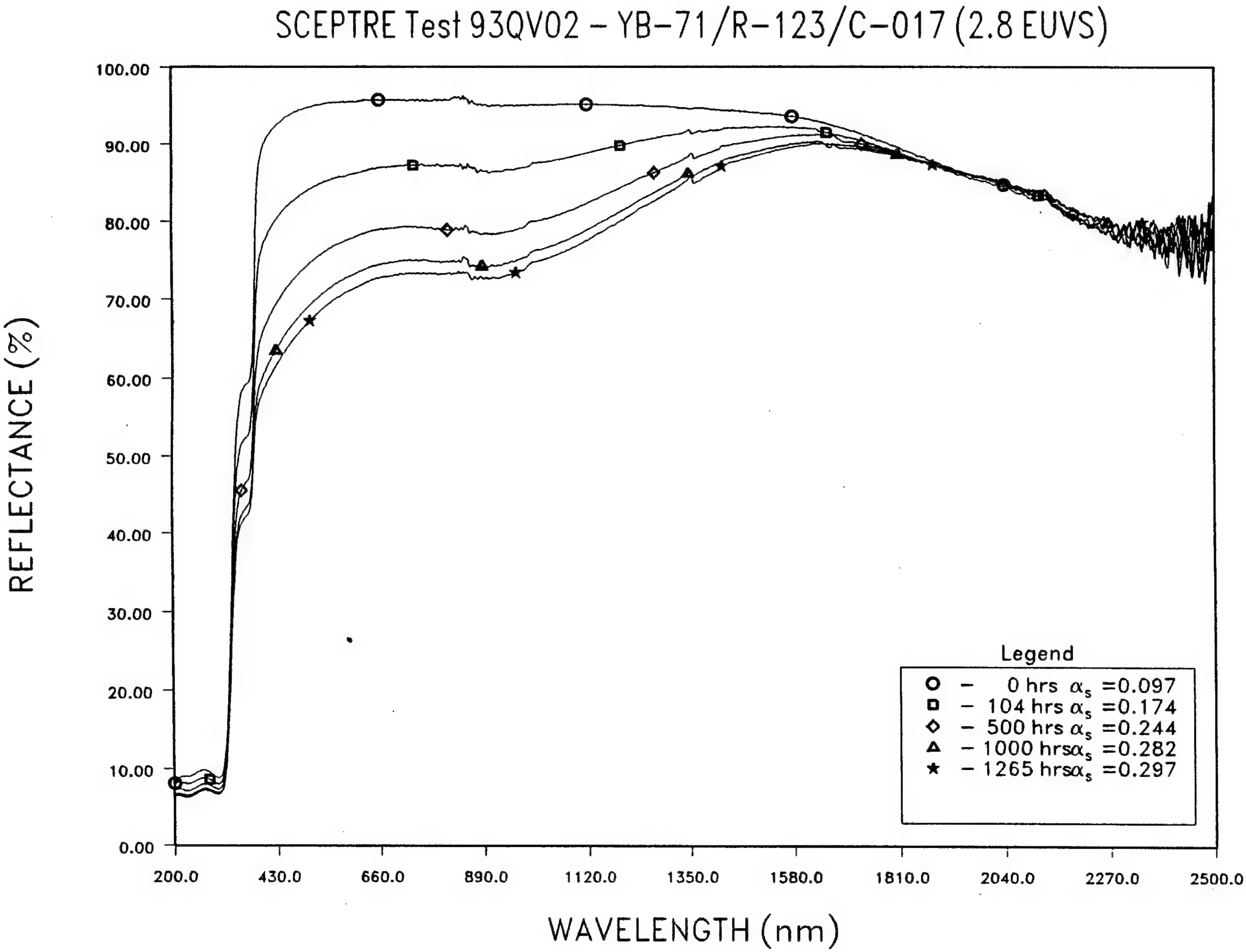

Figure B-8. SCEPTRE Test 93QV02 YB-71 (R-123) (2.8 EUVS) Reflectance Spectra History.

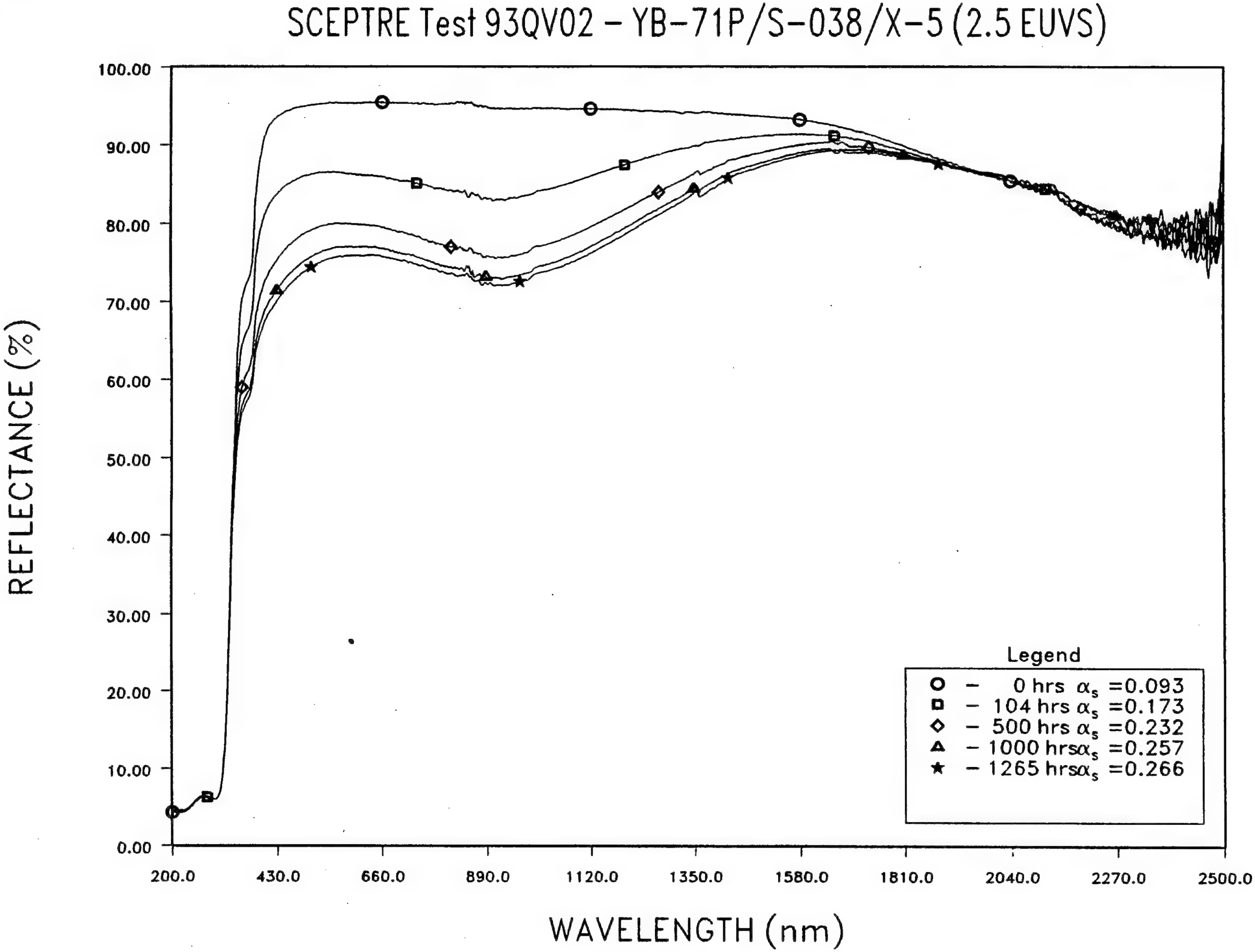

Figure B-9. SCEPTRE Test 93QV02 YB-71P (S-038) (2.5 EUVS) Reflectance Spectra History.

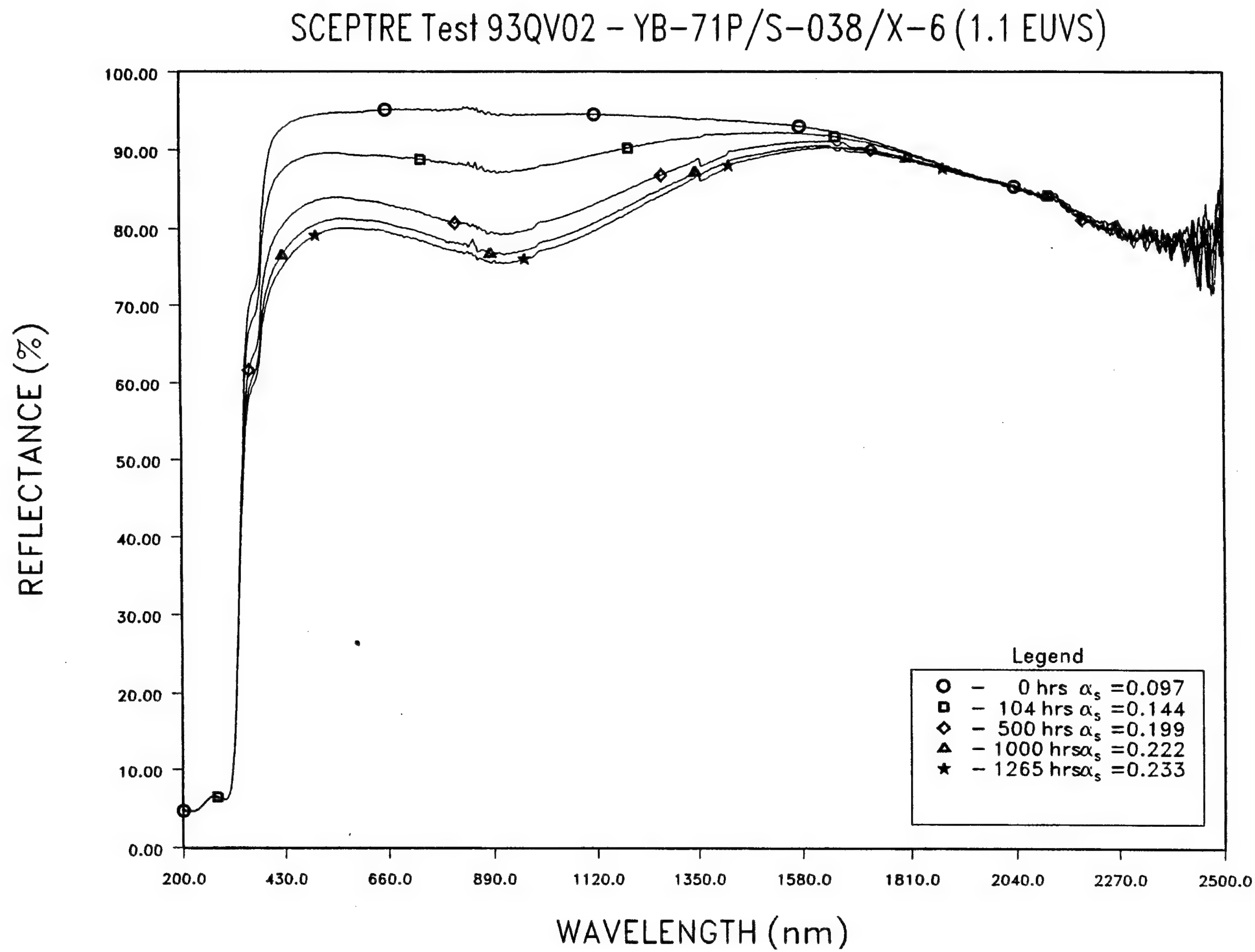

Figure B-10. SCEPTRE Test 93QV02 YB-71P (S-038) (1.1 EUVS) Reflectance Spectra History.

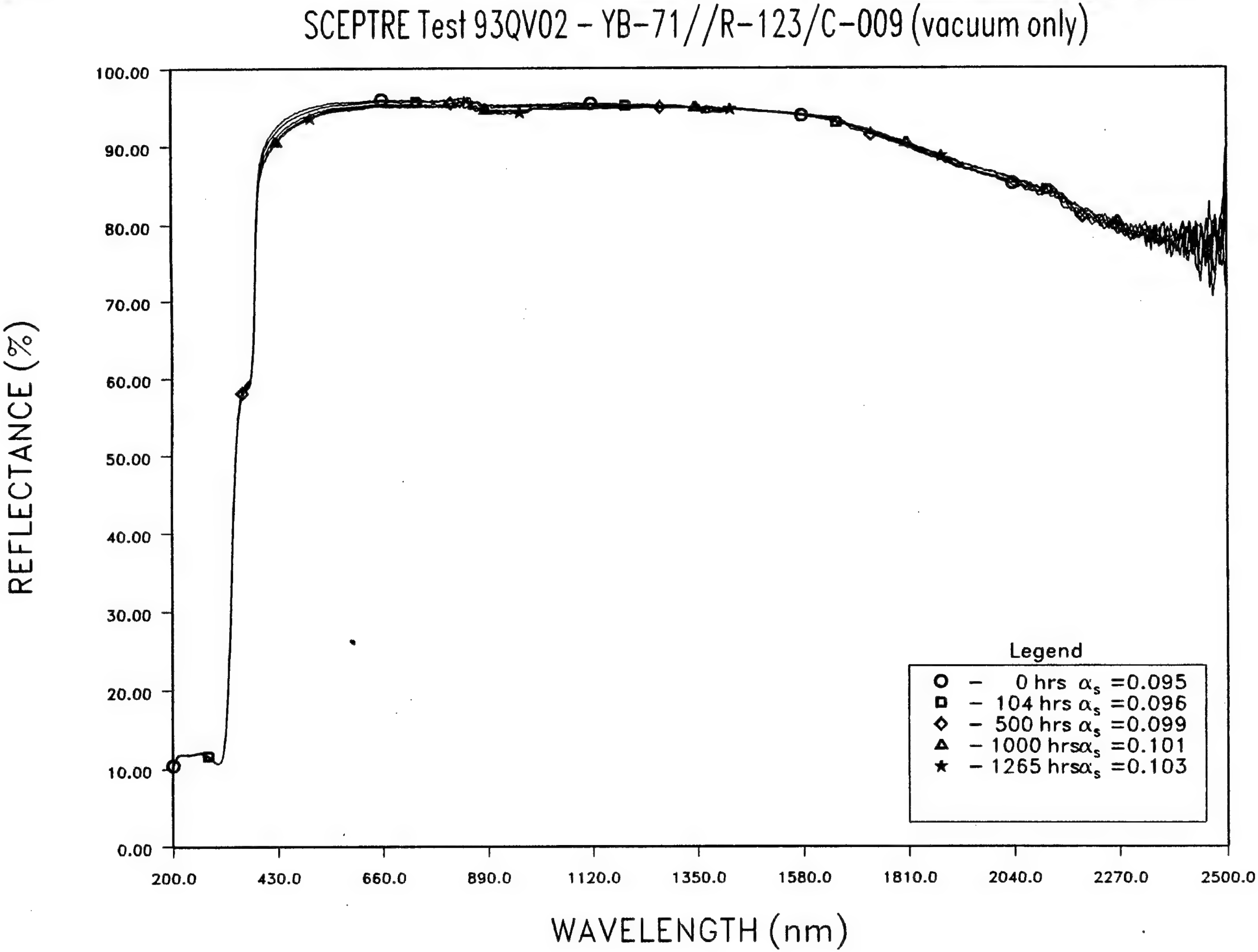

Figure B-11. SCEPTRE Test 93QV02 YB-71 (R-123) (reference) Reflectance Spectra History.

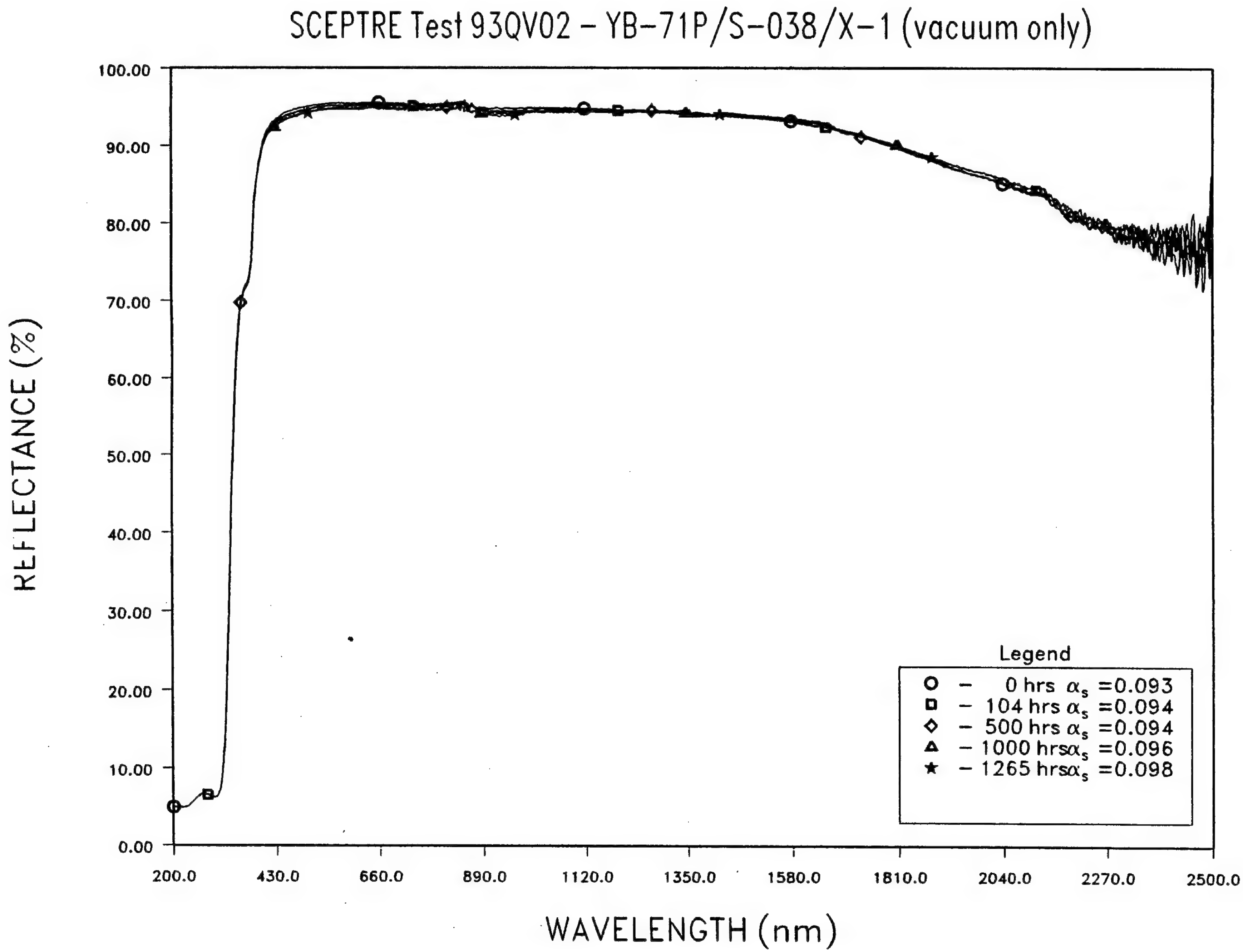

Figure B-12. SCEPTRE Test 93QV02 YB-71P (S-038) (reference) Reflectance Spectra History.

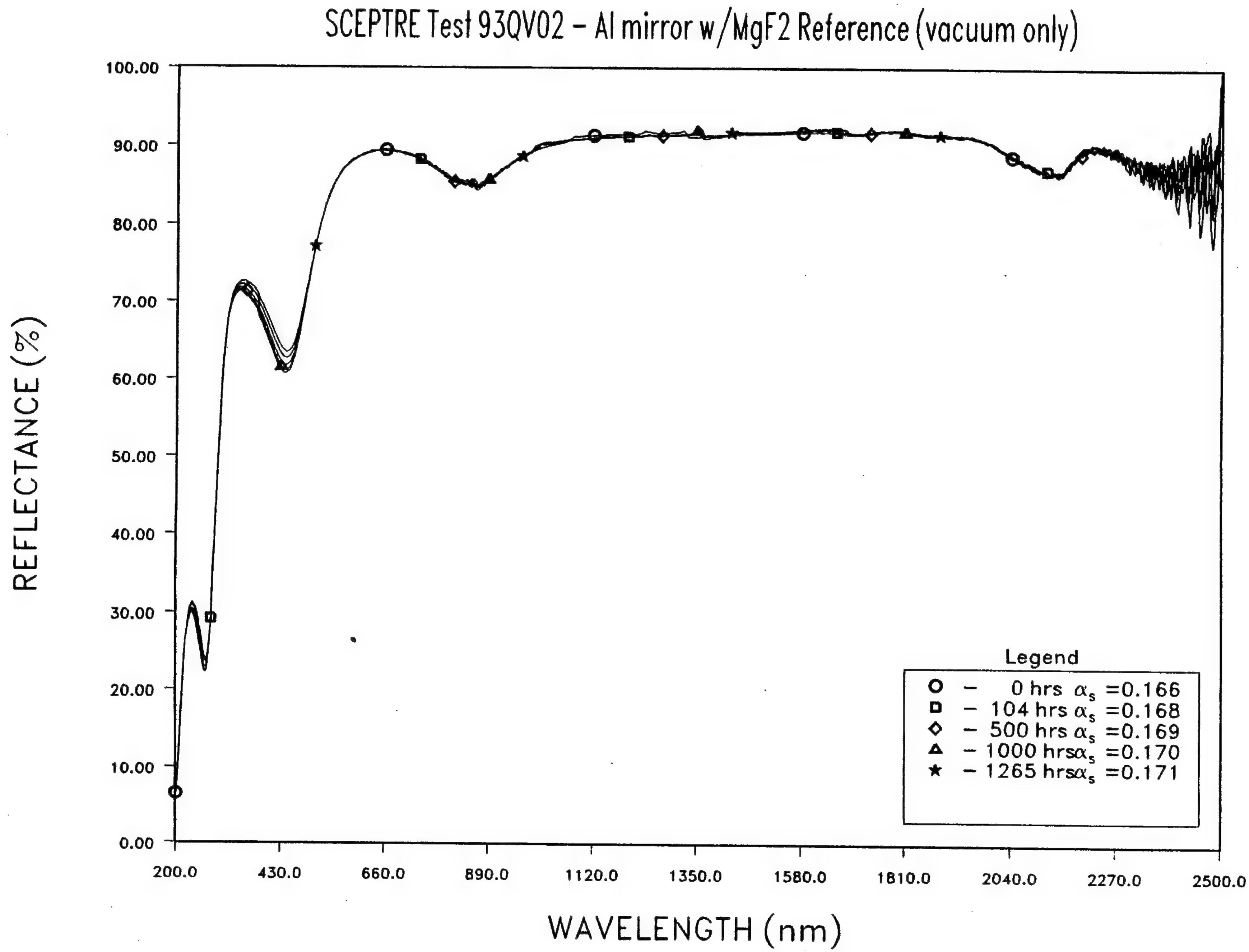

Figure B-13. SCEPTRE Test 93QV02 Al mirror w/MgF_2 (reference) Reflectance Spectra History.

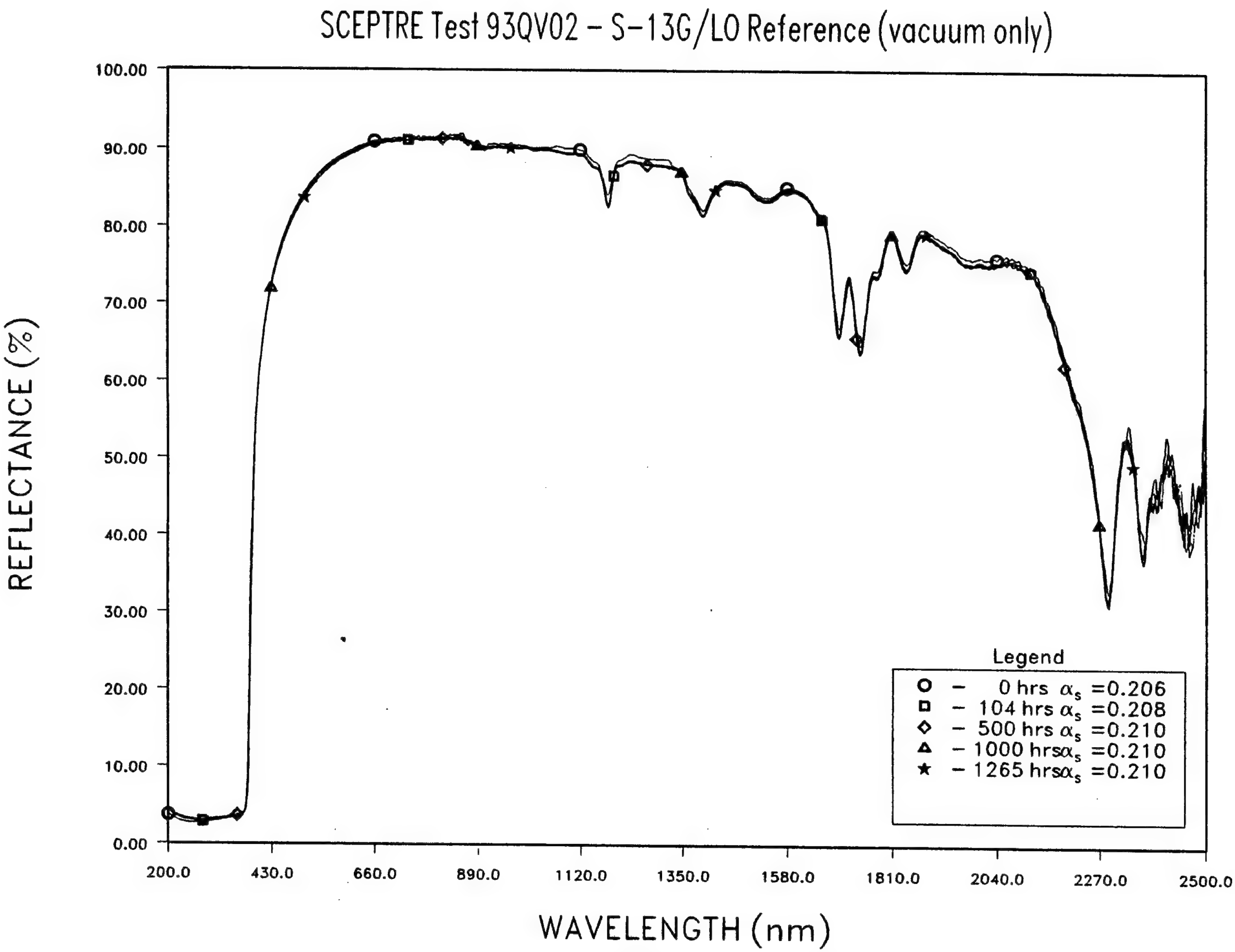

Figure B-14. SCEPTRE Test 93QV02 S-13G/LO (reference) Reflectance Spectra History.

APPENDIX C

SUPPLEMENTAL DATA FOR SCEPTRE 94QV01 TEST

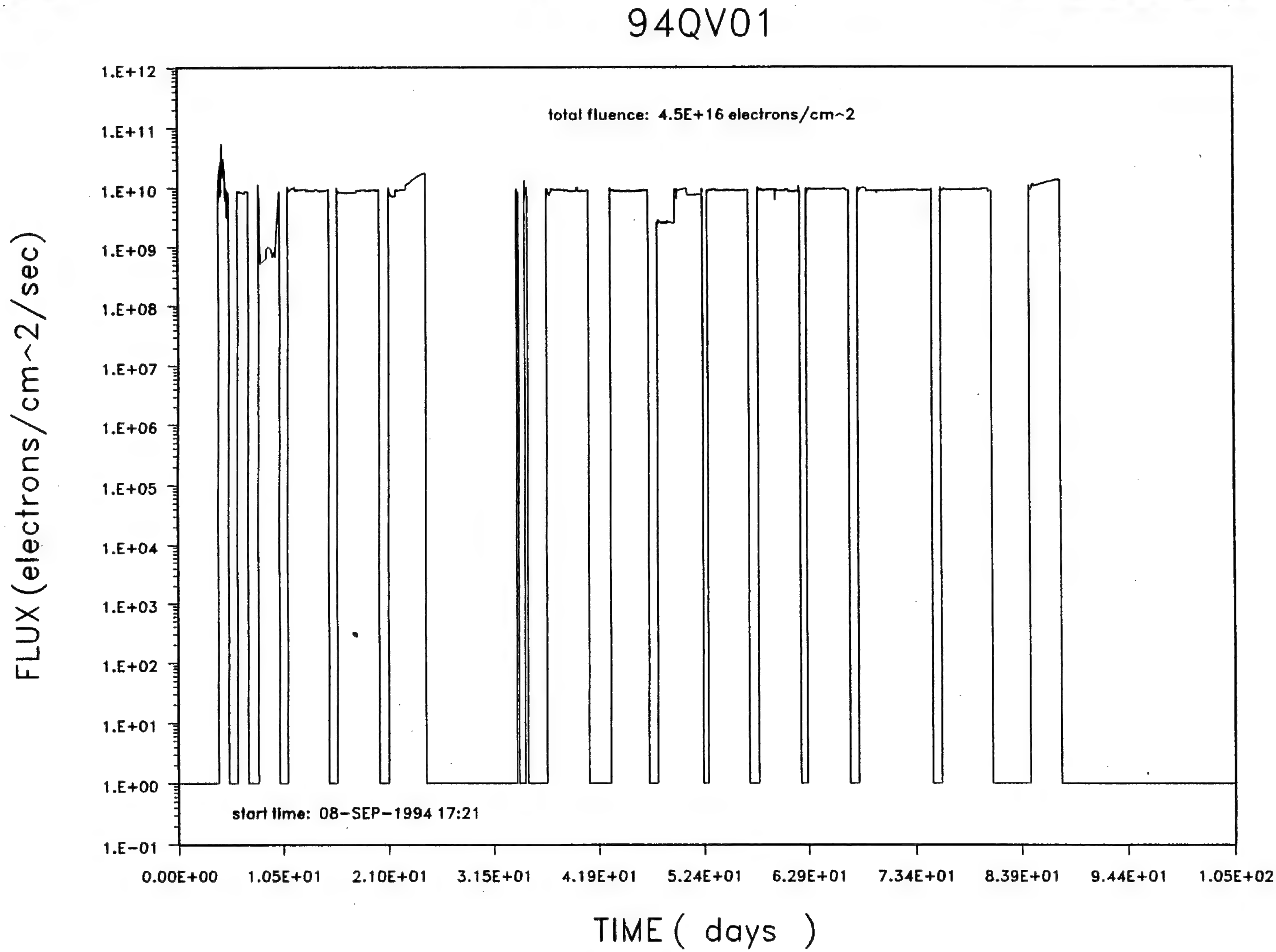

Figure C-1. SCEPTRE Test 94QV01 Electron Flux History.

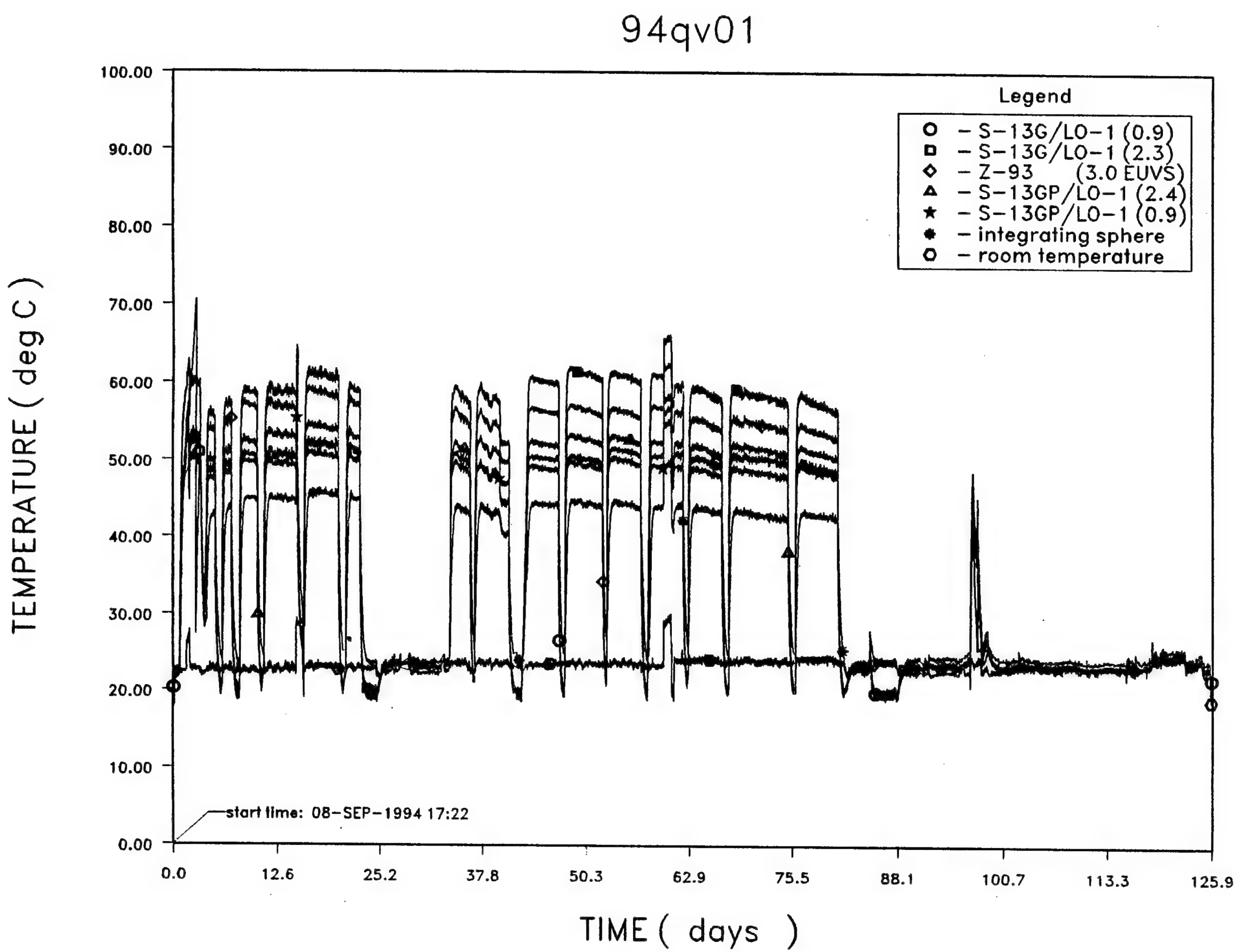

Figure C-2. SCEPTRE Test 94QV01 Specimen Temperature History.

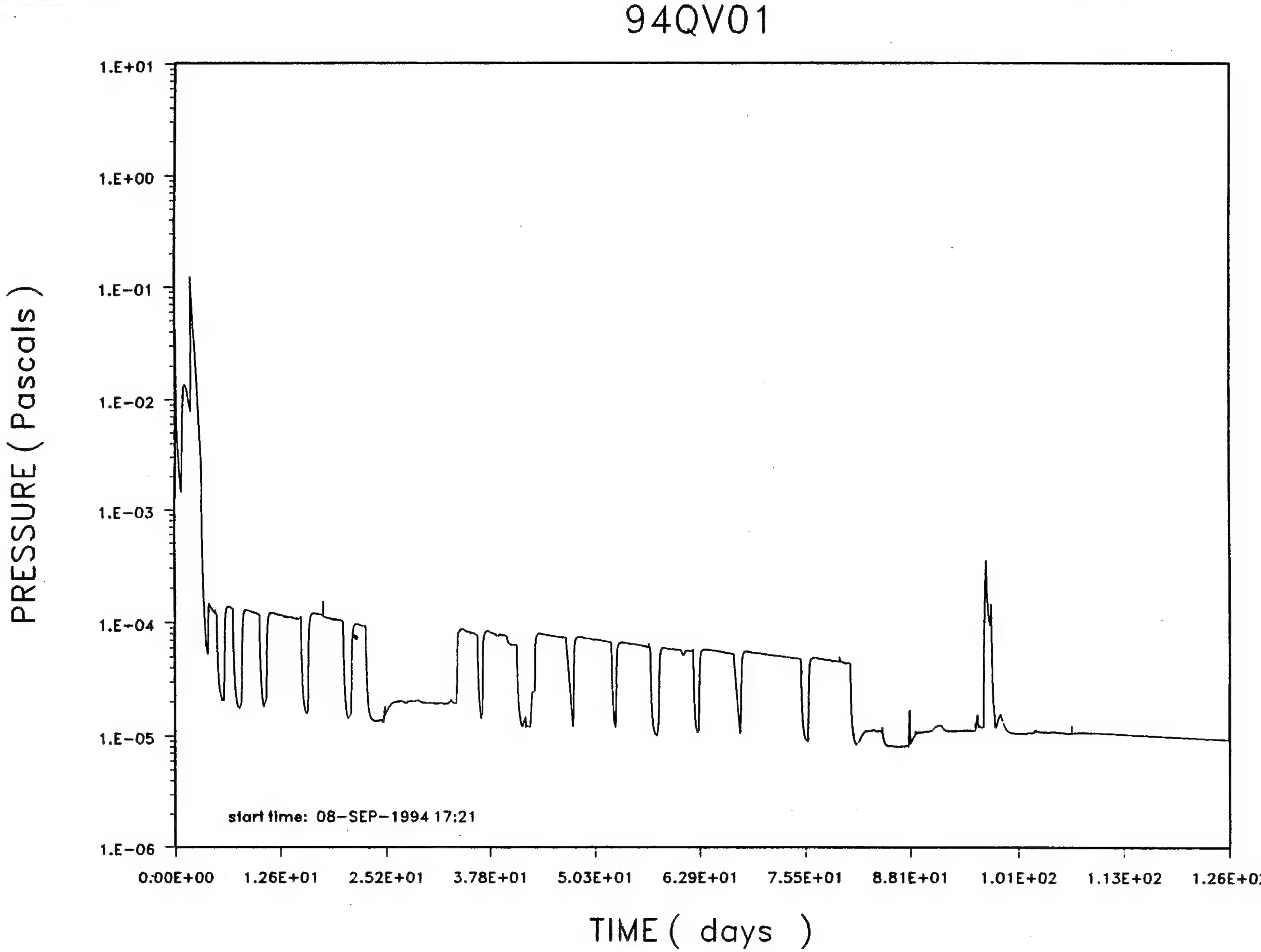

Figure C-3. SCEPTRE Test 94QV01 Granville-Phillips Ion Gauge Vacuum Level History.

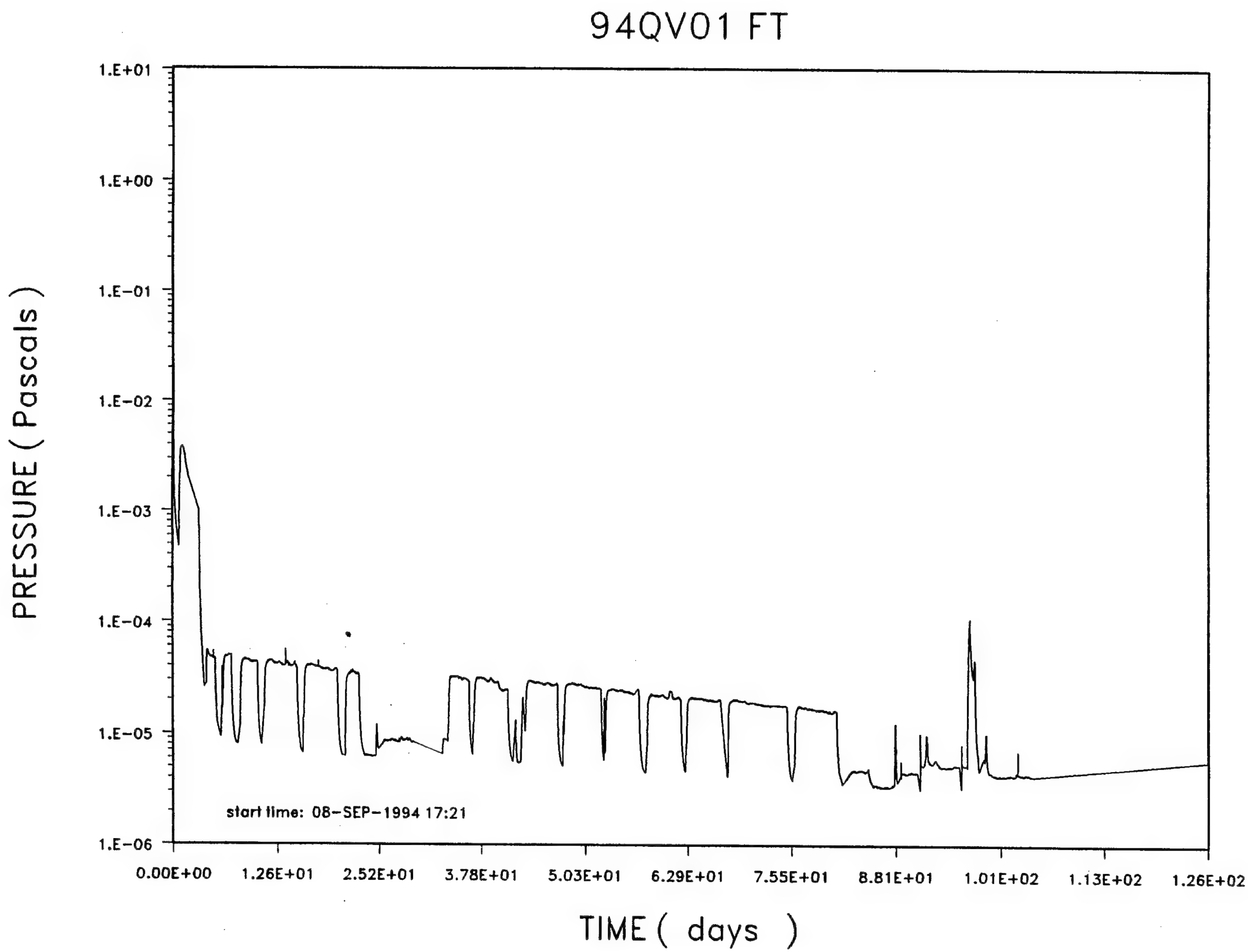

Figure C-4. SCEPTRE Test 94QV01 Fredricks-Televac Ion Gauge Vacuum Level History.

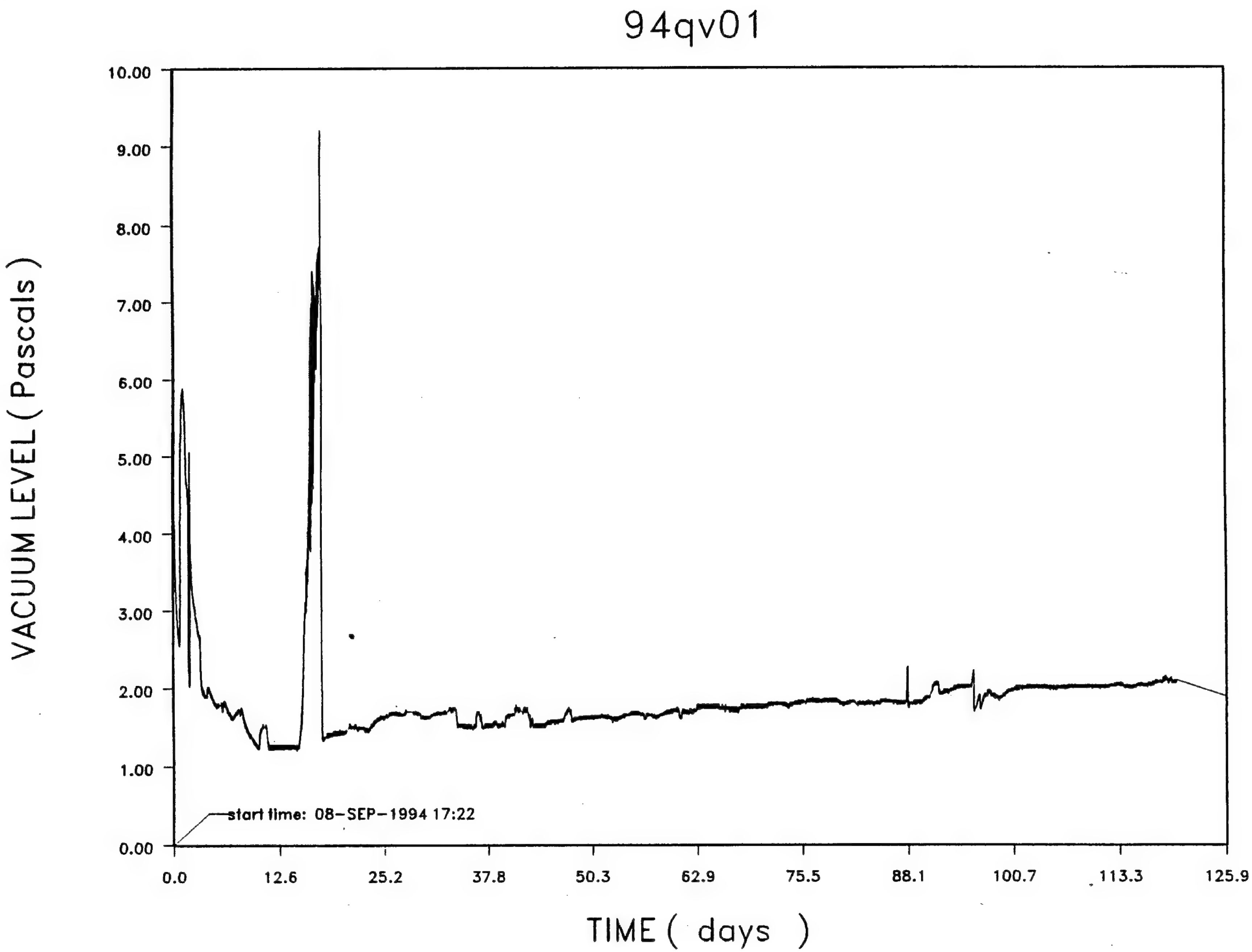

Figure C-5. SCEPTRE Test 94QV01 Foreline Thermocouple Gauge Vacuum Level History.

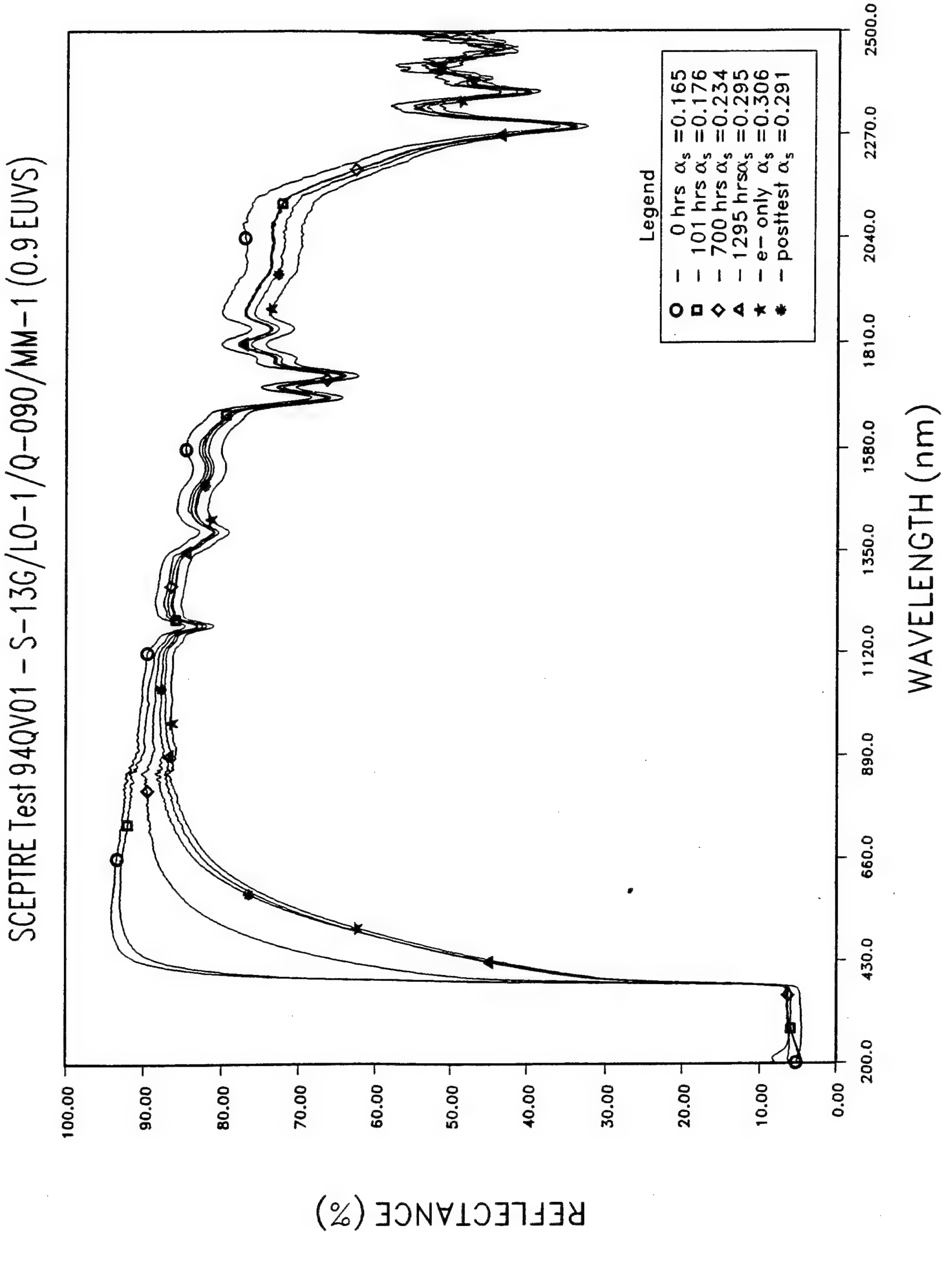

Figure C-6. SCEPTRE Test 94QV01 S-13G/LO-1 (Q-090) (0.9 EUVS) Reflectance Spectra History.

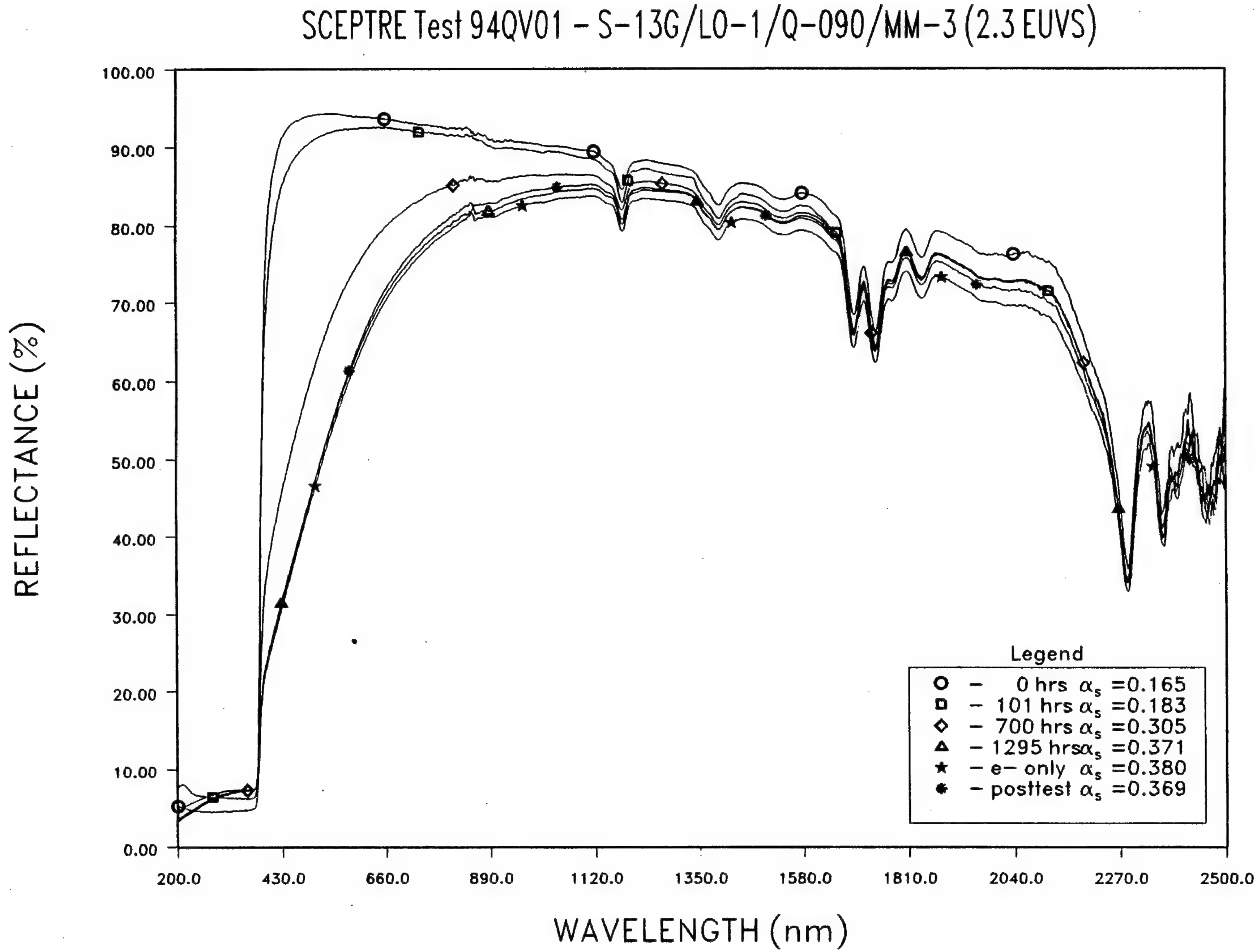

Figure C-7. SCEPTRE Test 94QV01 S-13G/LO-1 (Q-090) (2.3 EUVS) Reflectance Spectra History.

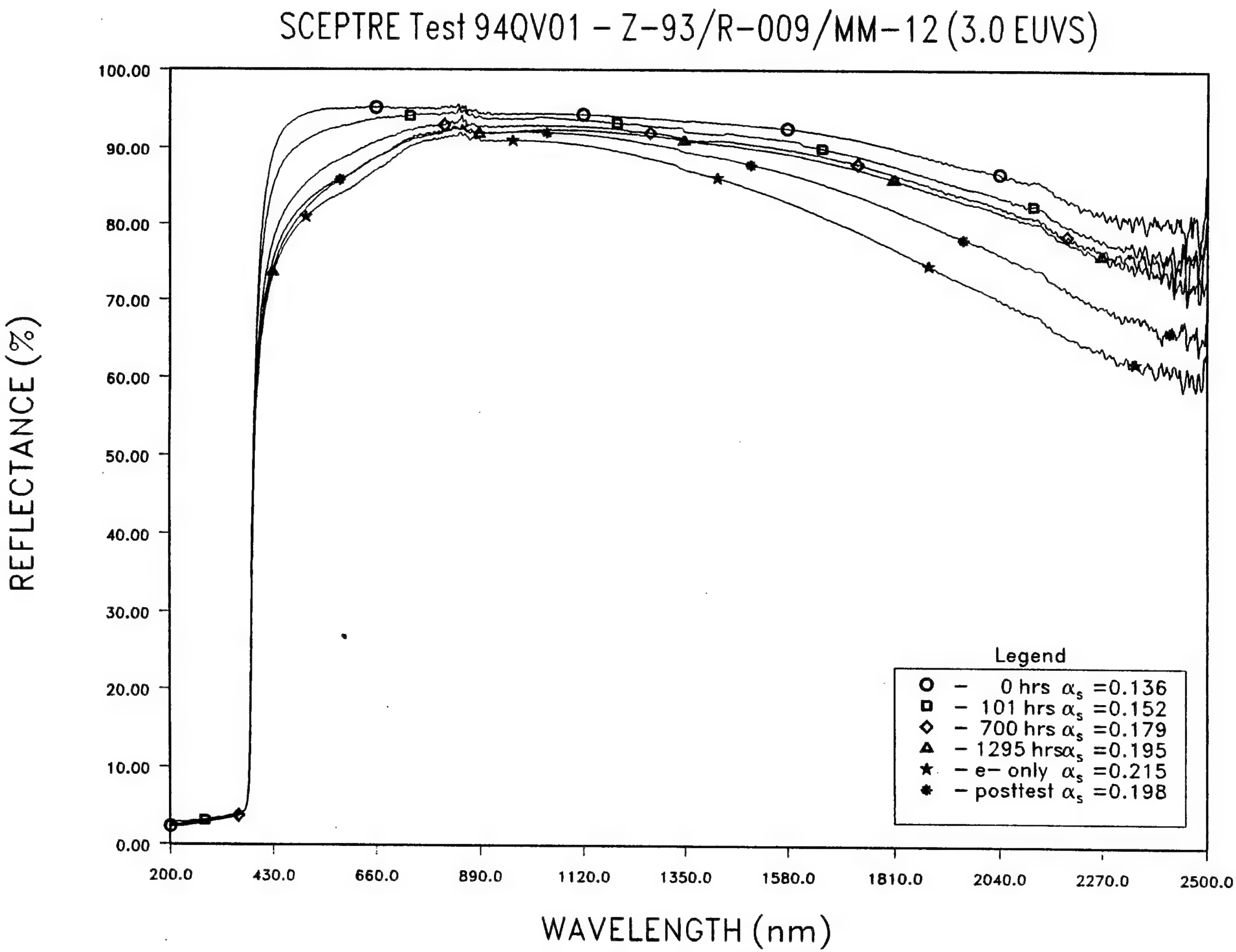

Figure C-8. SCEPTRE Test 94QV01 Z-93 (R-009) (3.0 EUVS) Reflectance Spectra History.

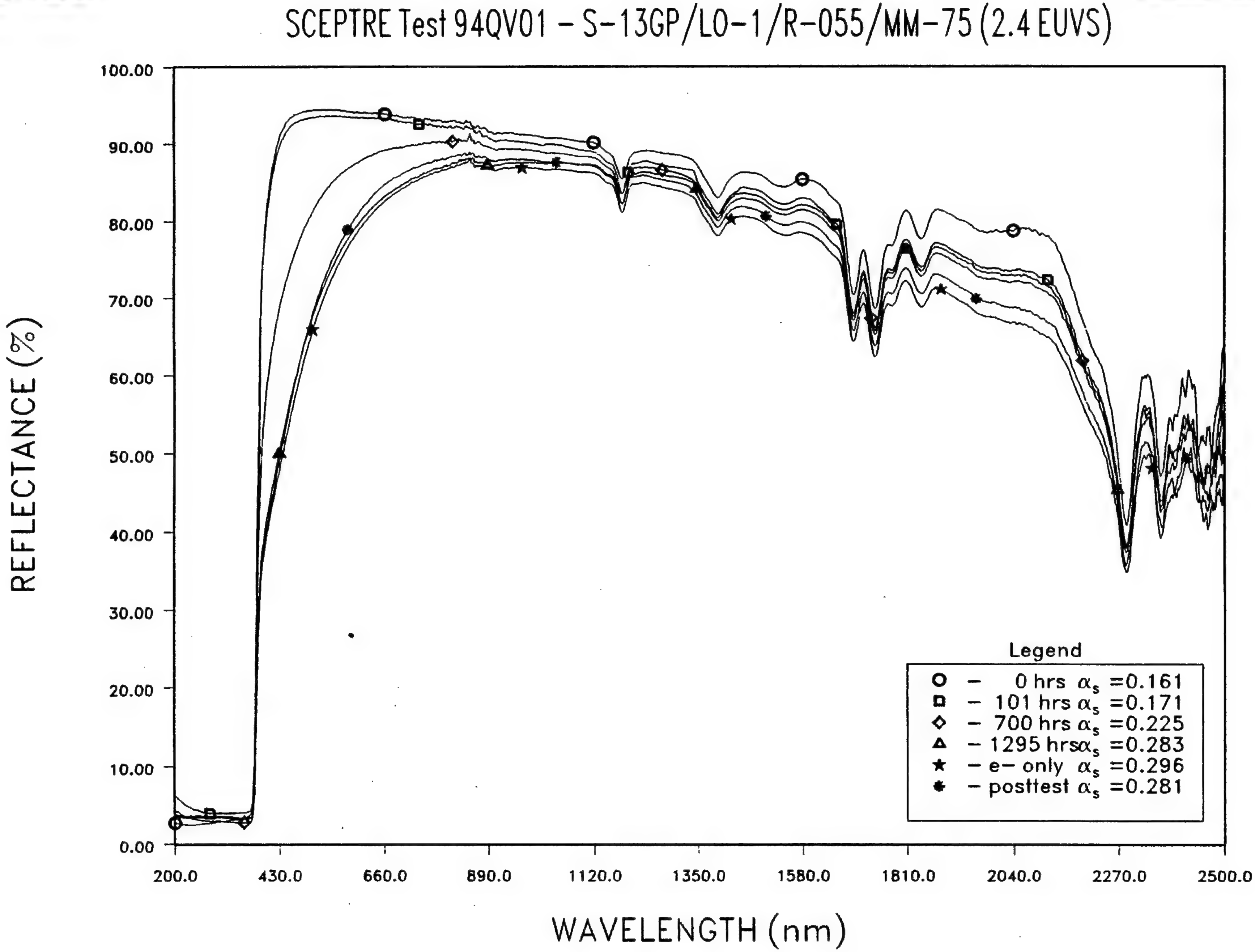

Figure C-9. SCEPTRE Test 94QV01 S-13GP/LO-1 (R-055) (2.4 EUVS) Reflectance Spectra History.

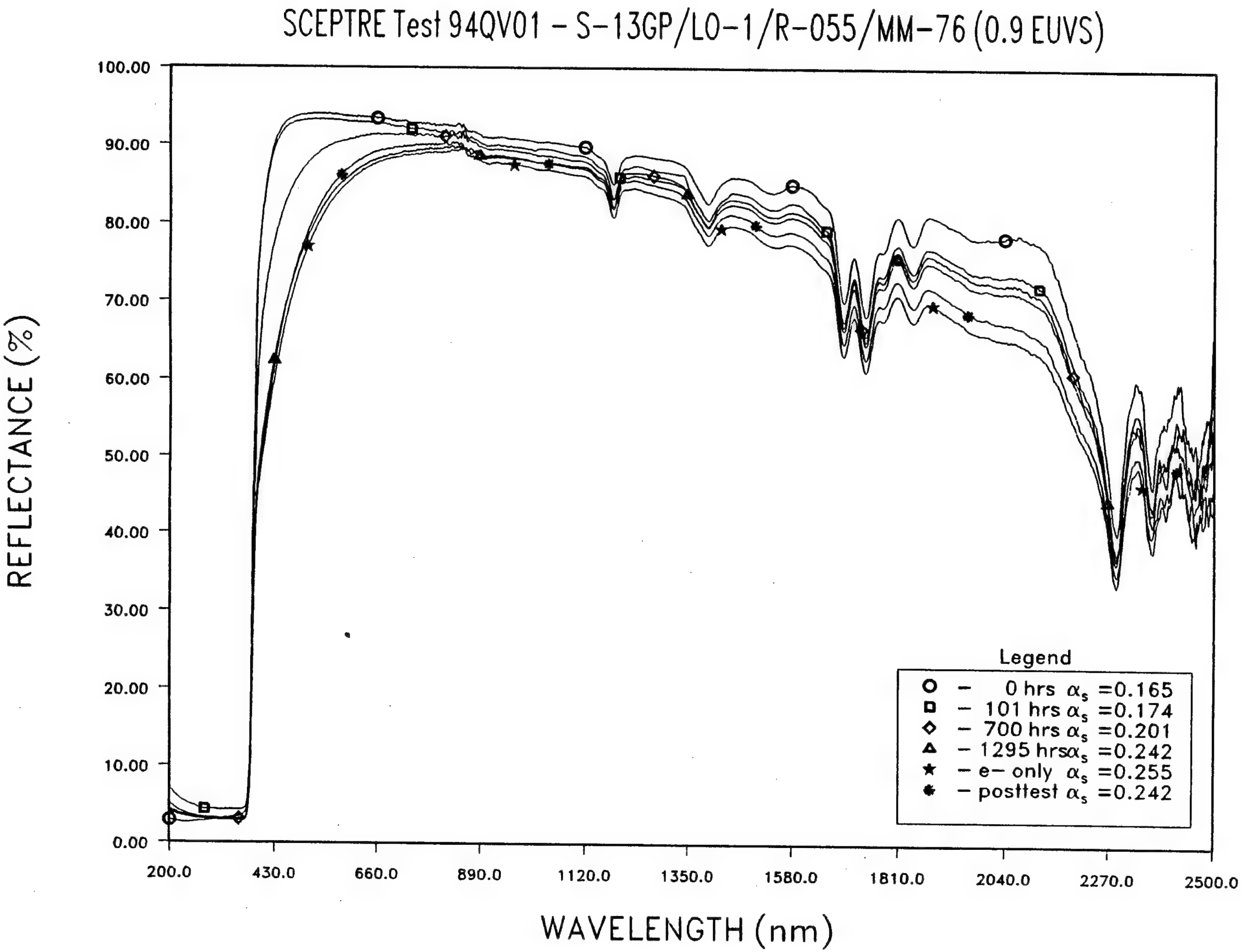

Figure C-10. SCEPTRE Test 94QV01 S-13GP/LO-1 (R-055) (0.9 EUVS) Reflectance Spectra History.

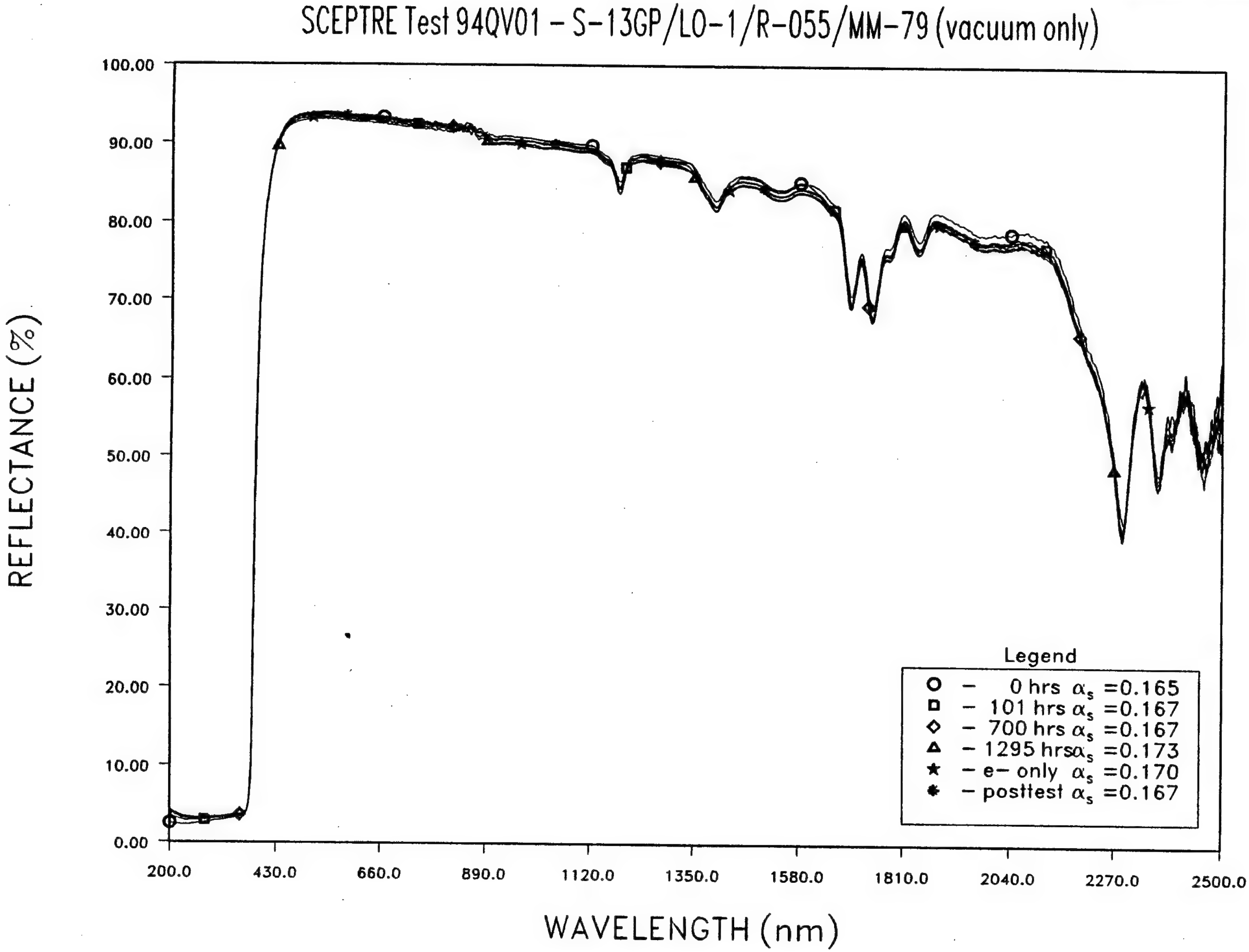

Figure C-11. SCEPTRE Test 94QV01 S-13GP/LO-1 (R-055) (reference) Reflectance Spectra History.

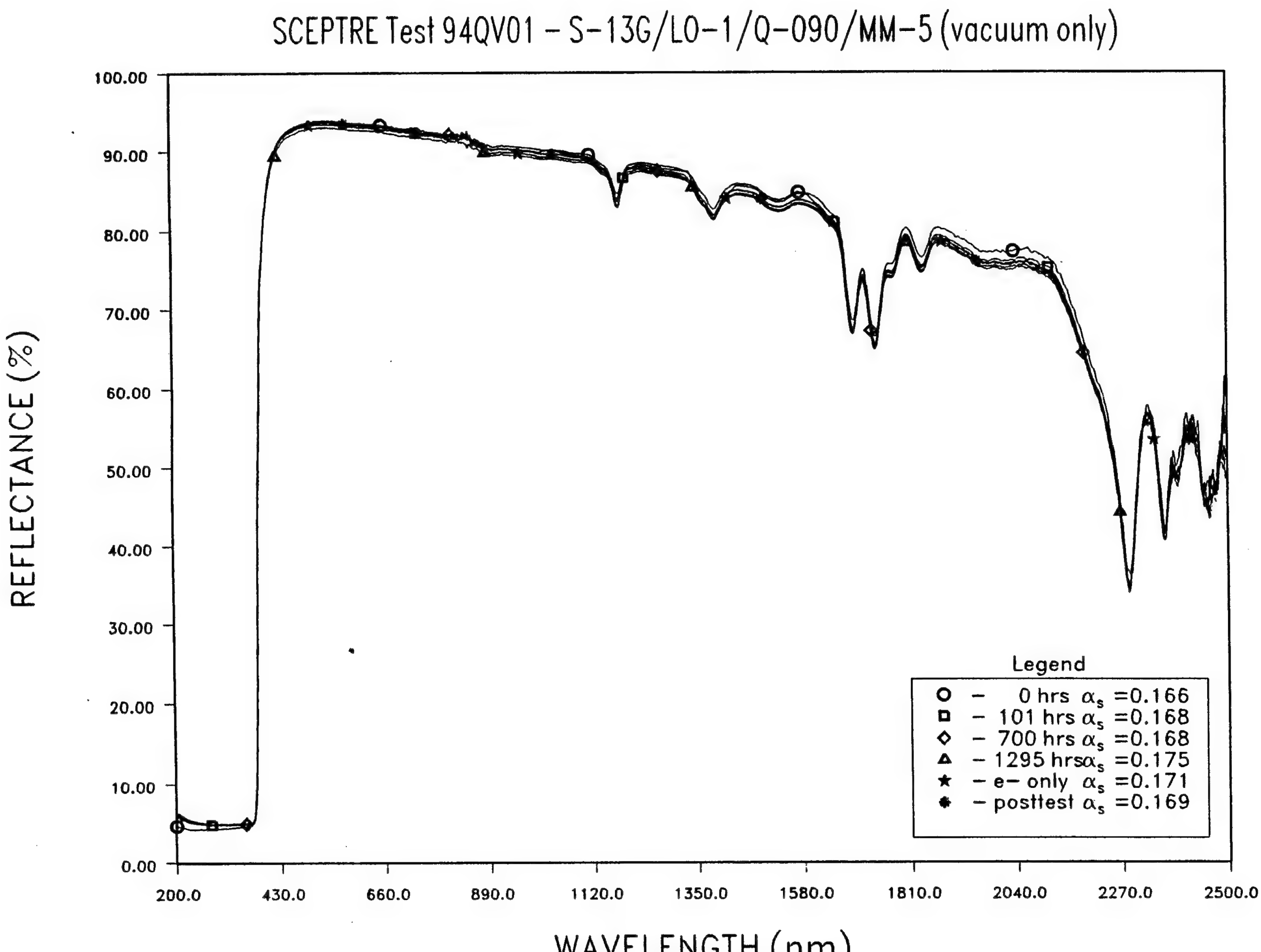

Figure C-12. SCEPTRE Test 94QV01 S-13G/LO-1 (Q-090) (reference) Reflectance Spectra History.

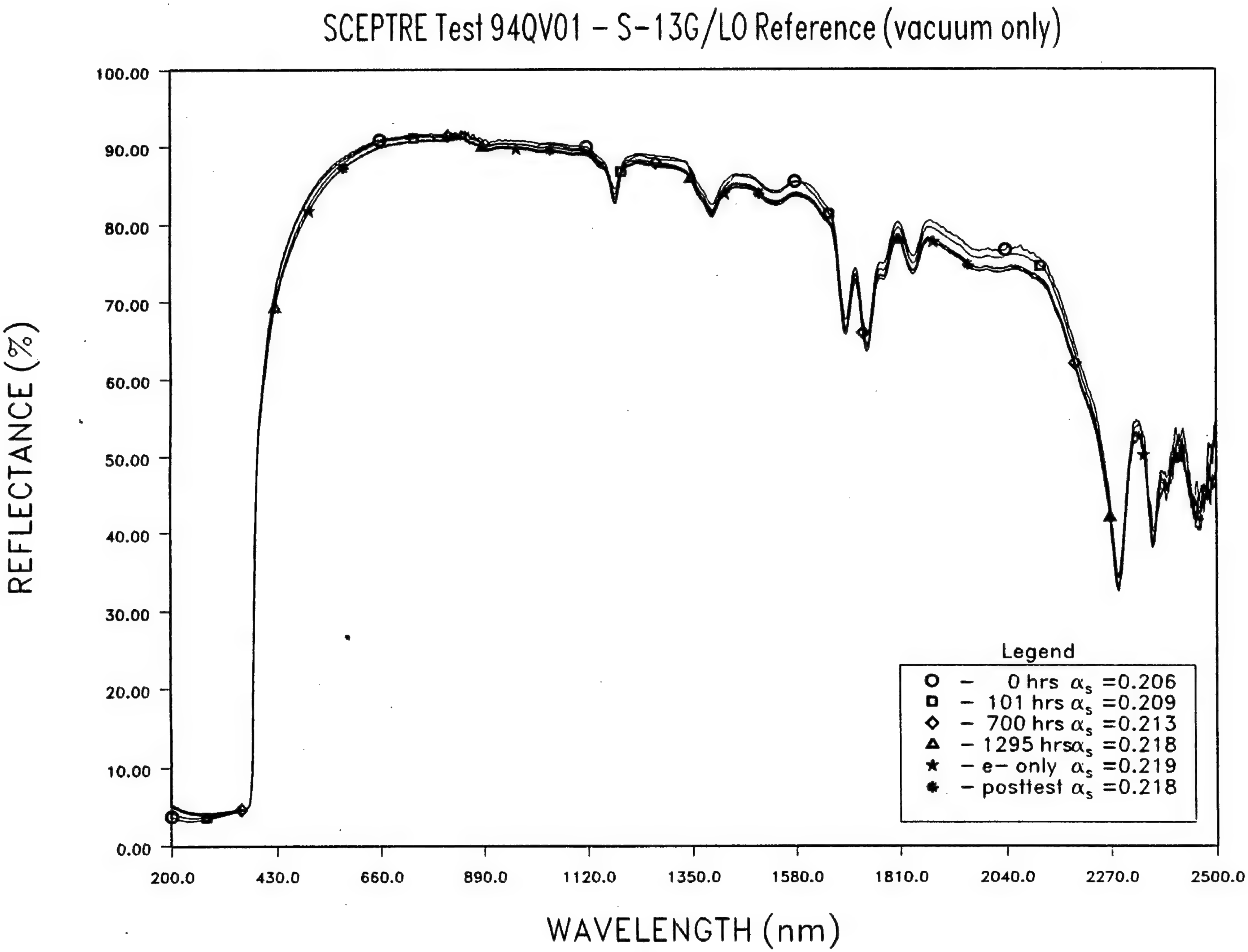

Figure C-13. SCEPTRE Test 94QV01 Al mirror w/MgF_2 (reference) Reflectance Spectra History.

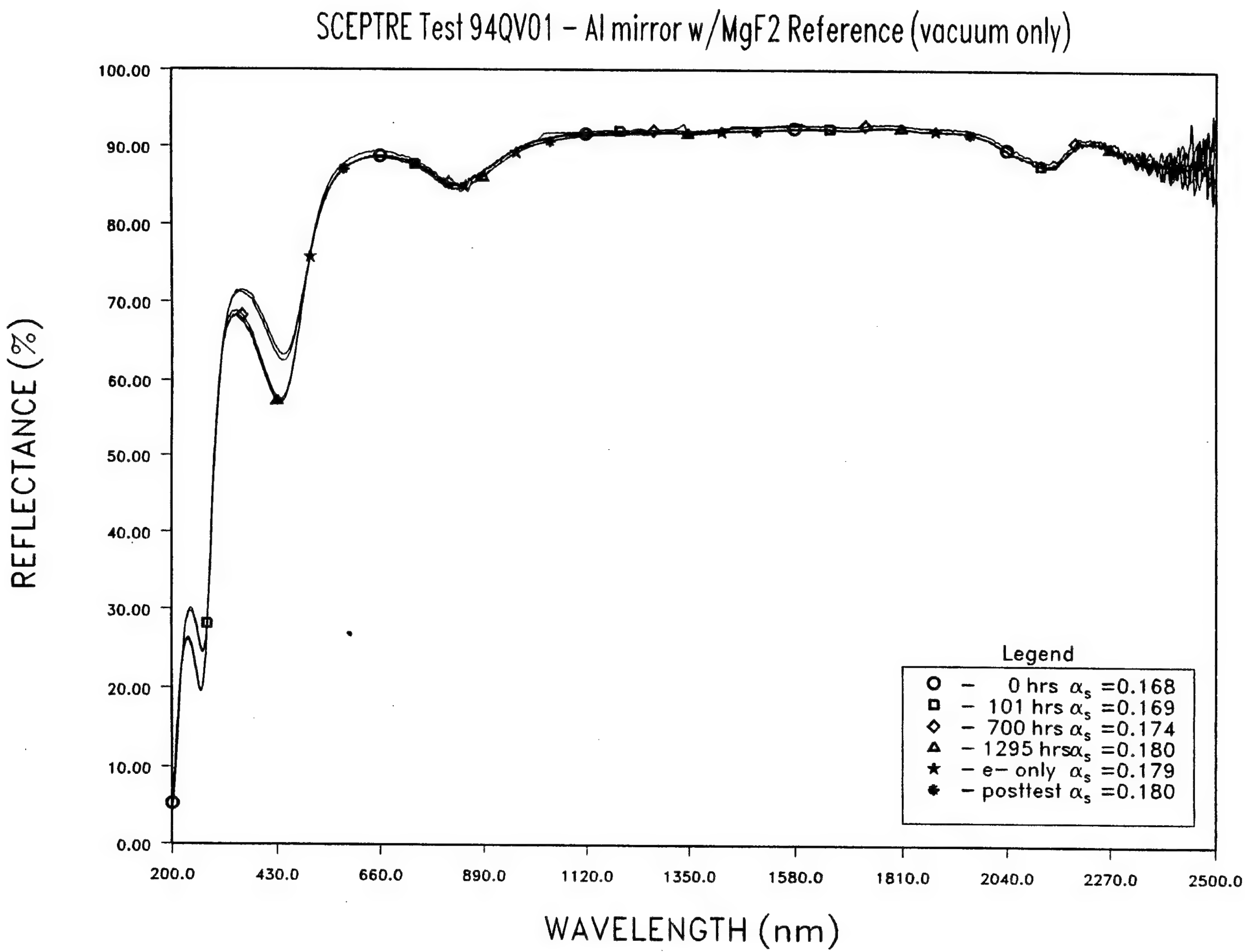

Figure C-14. SCEPTRE Test 94QV01 S-13G/LO (reference) Reflectance Spectra History.

APPENDIX D

SUPPLEMENTAL DATA FOR SCEPTRE 95QV01 TEST

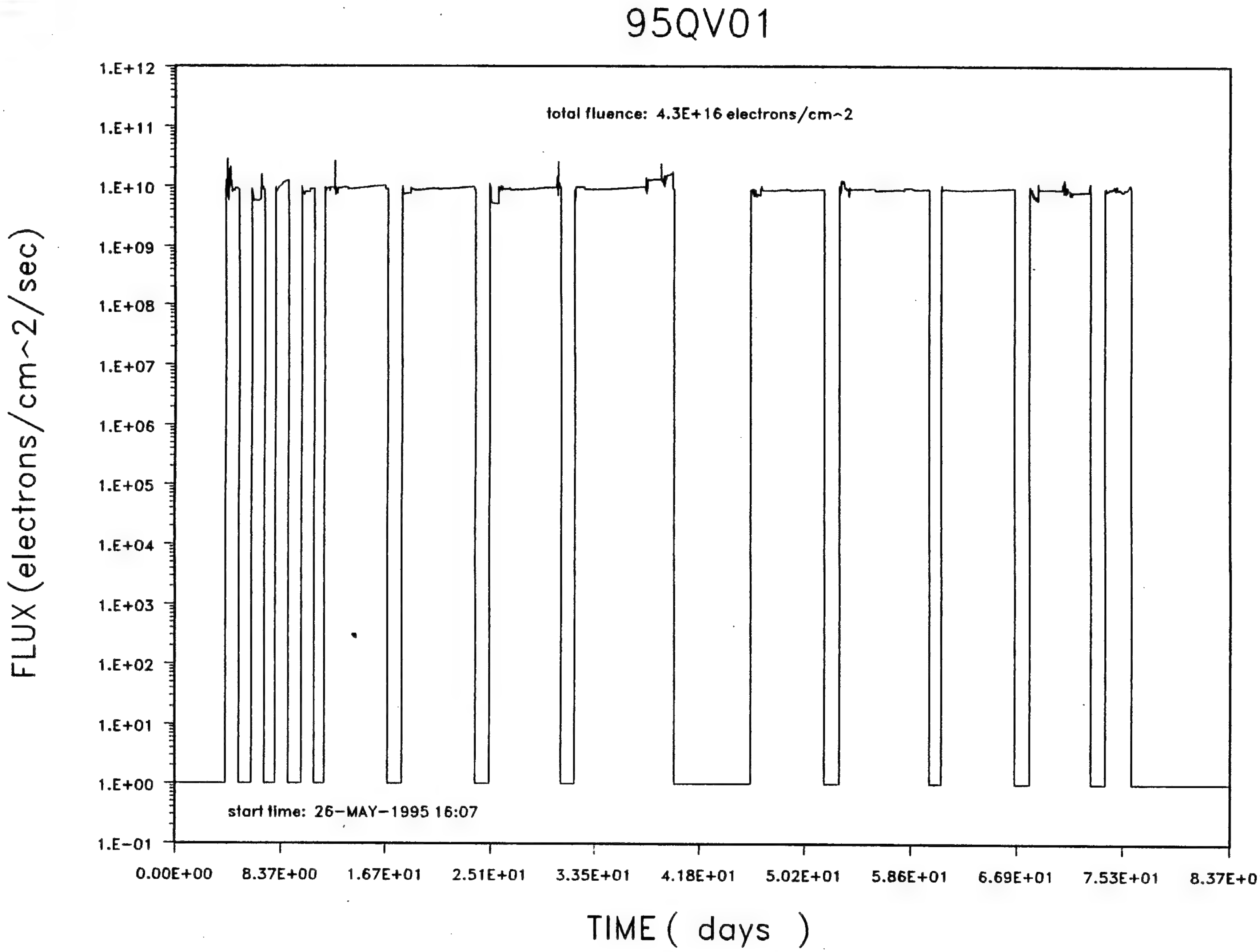

Figure D-1. SCEPTRE Test 95QV01 Electron Flux History.

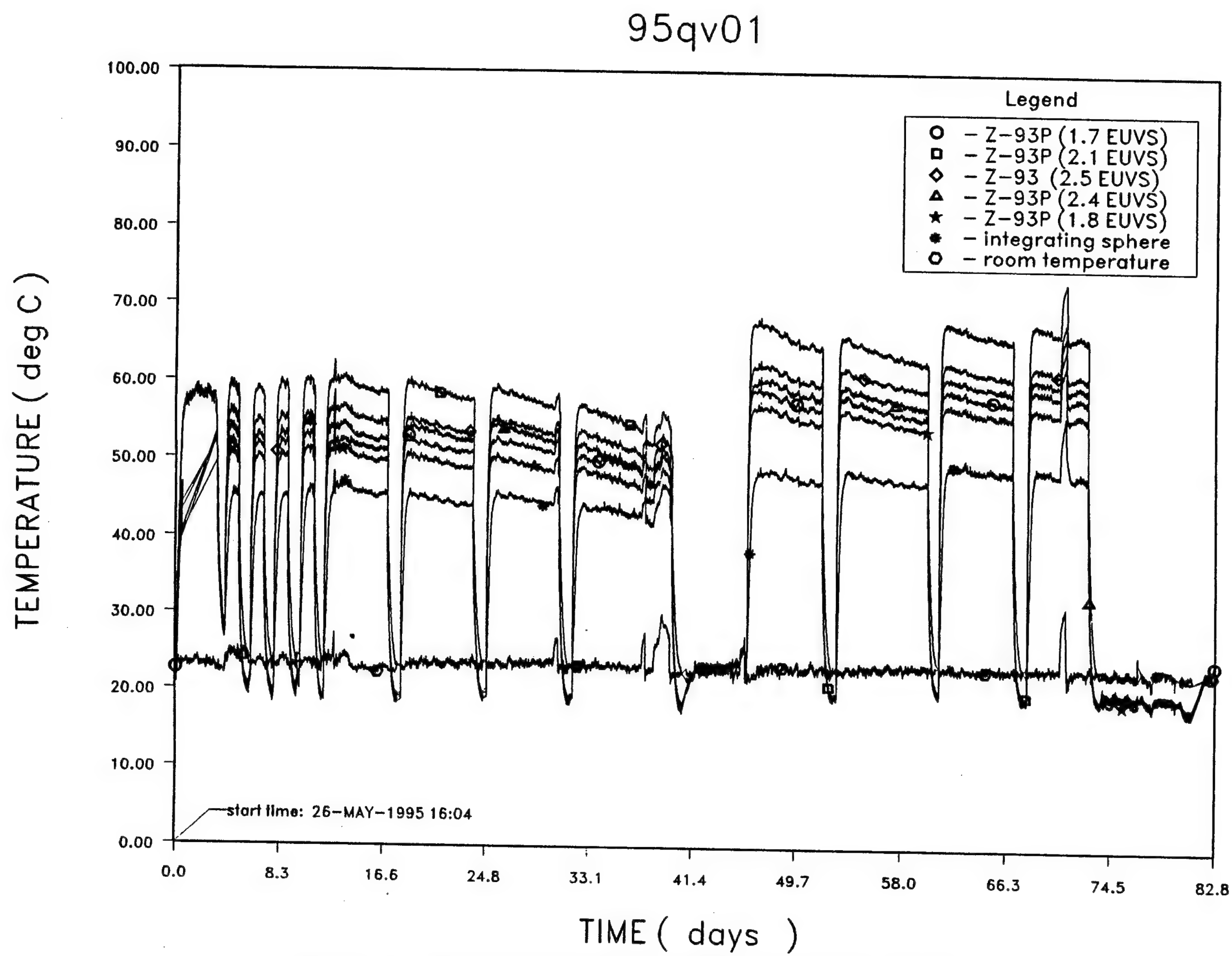

Figure D-2. SCEPTRE Test 95QV01 Specimen Temperature History.

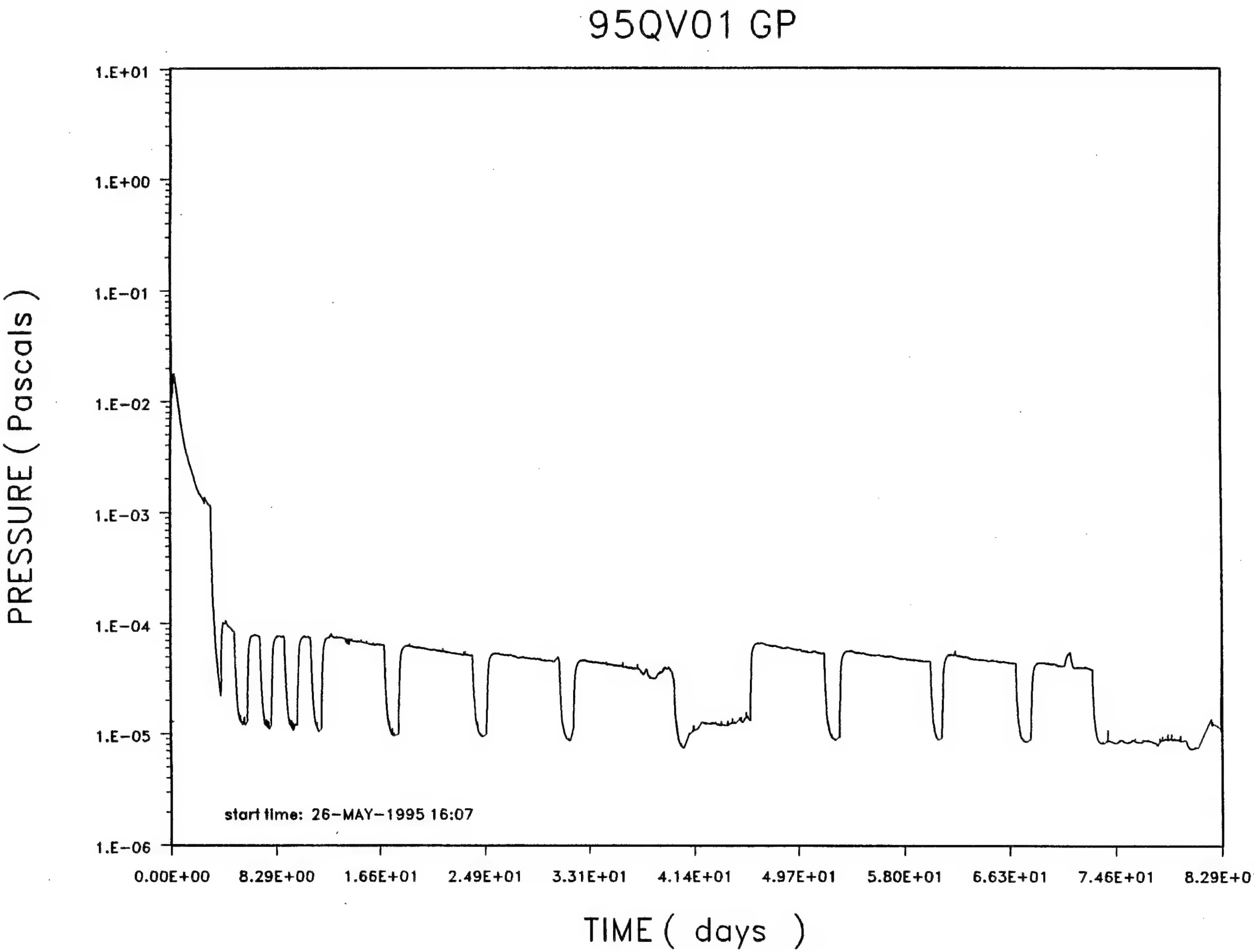

Figure D-3. SCEPTRE Test 95QV01 Granville-Phillips Ion Gauge Vacuum Level History.

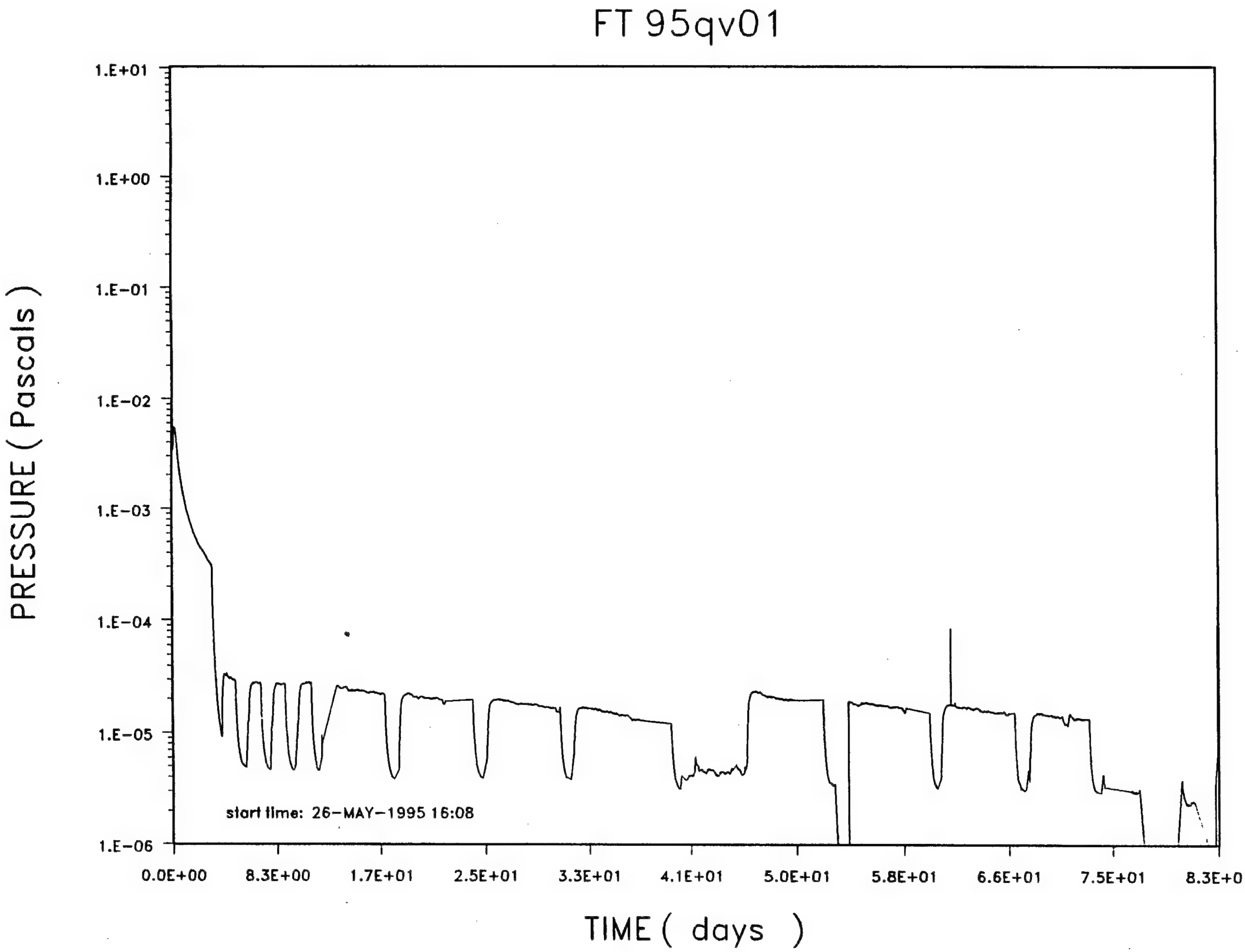

Figure D-4. SCEPTRE Test 95QV01 Fredricks-Televac Ion Gauge Vacuum Level History.

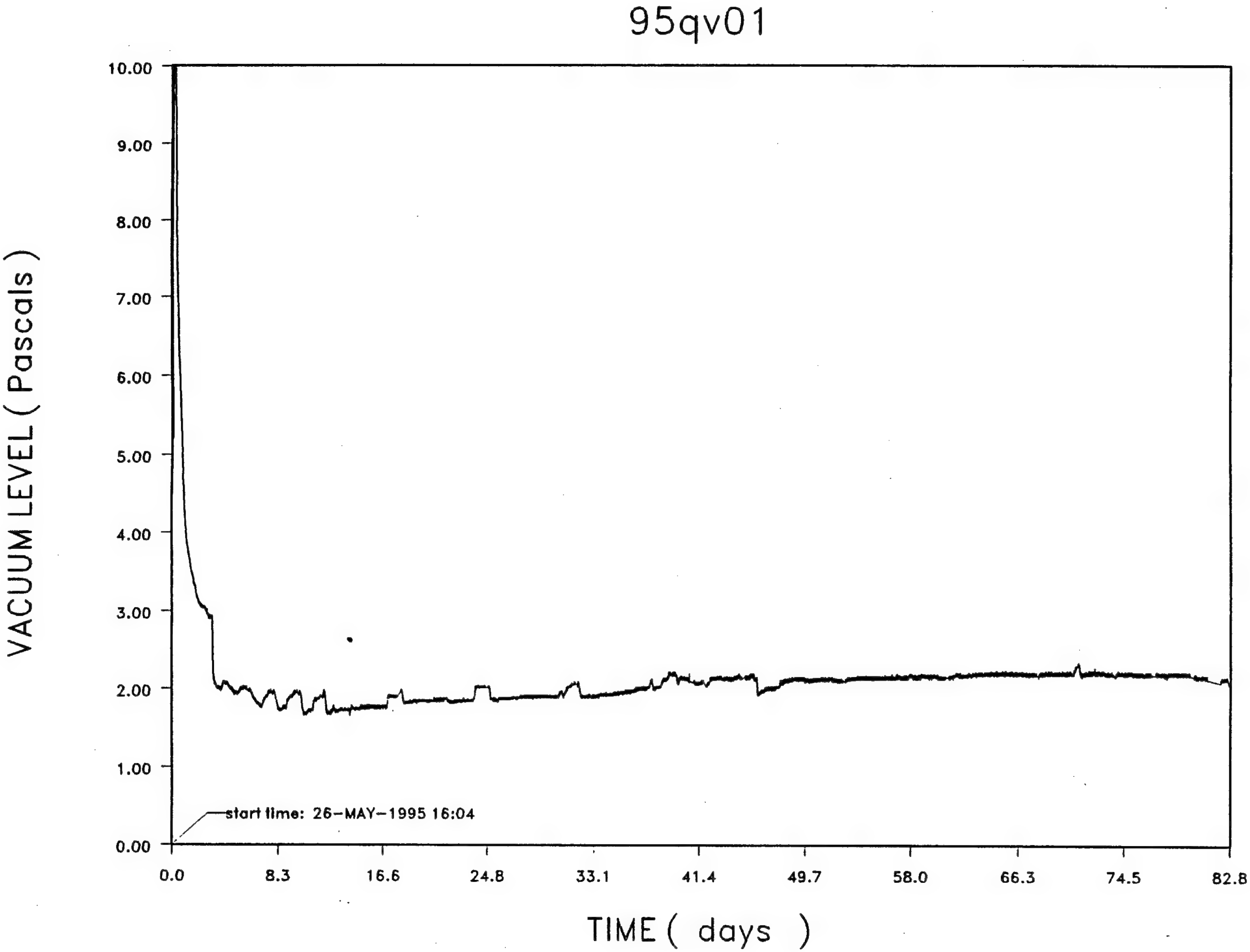

Figure D-5. SCEPTRE Test 95QV01 Foreline Thermocouple Gauge Vacuum Level History.

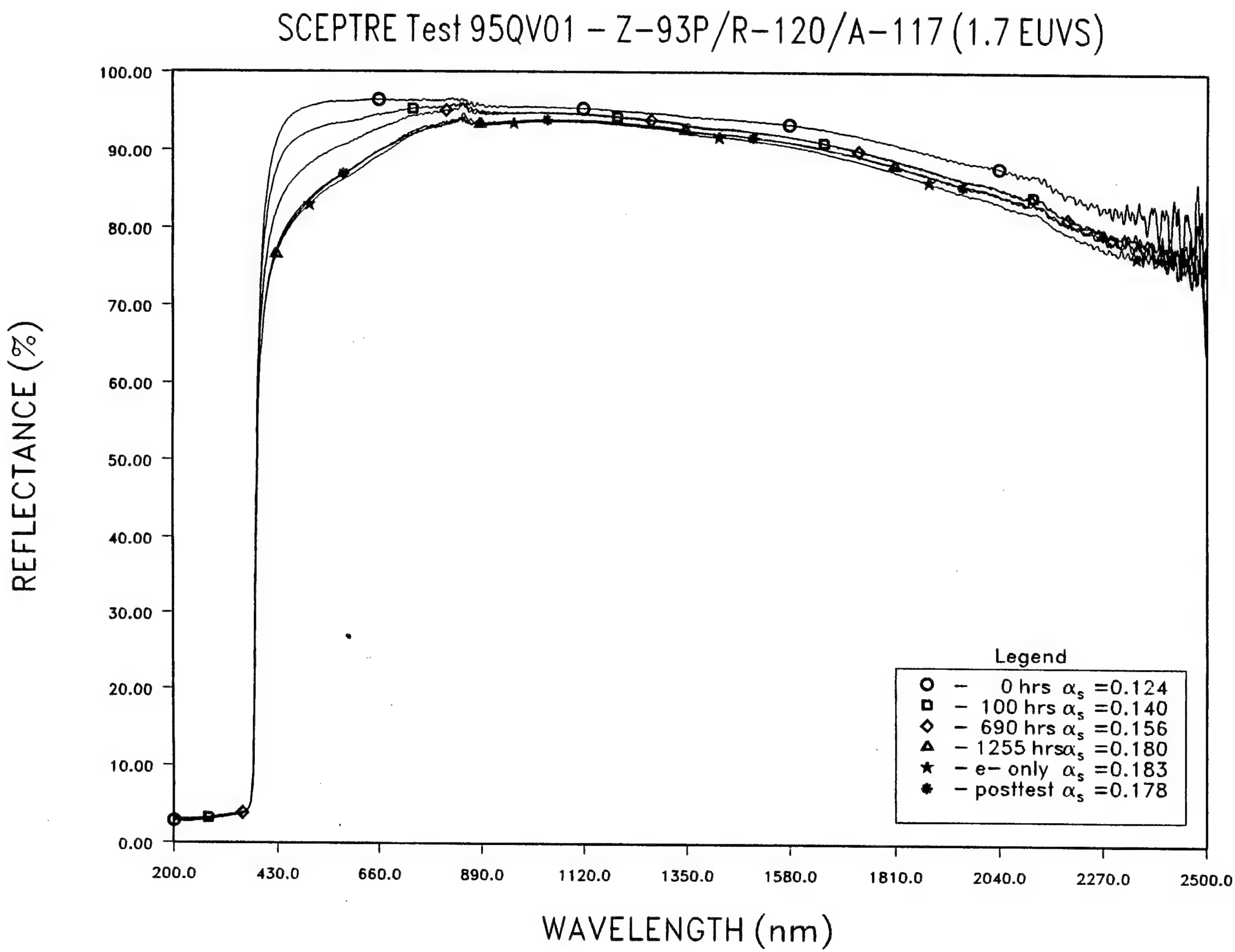

Figure D-6. SCEPTRE Test 95QV01 Z-93P (R-120) (1.7 EUVS) Reflectance Spectra History.

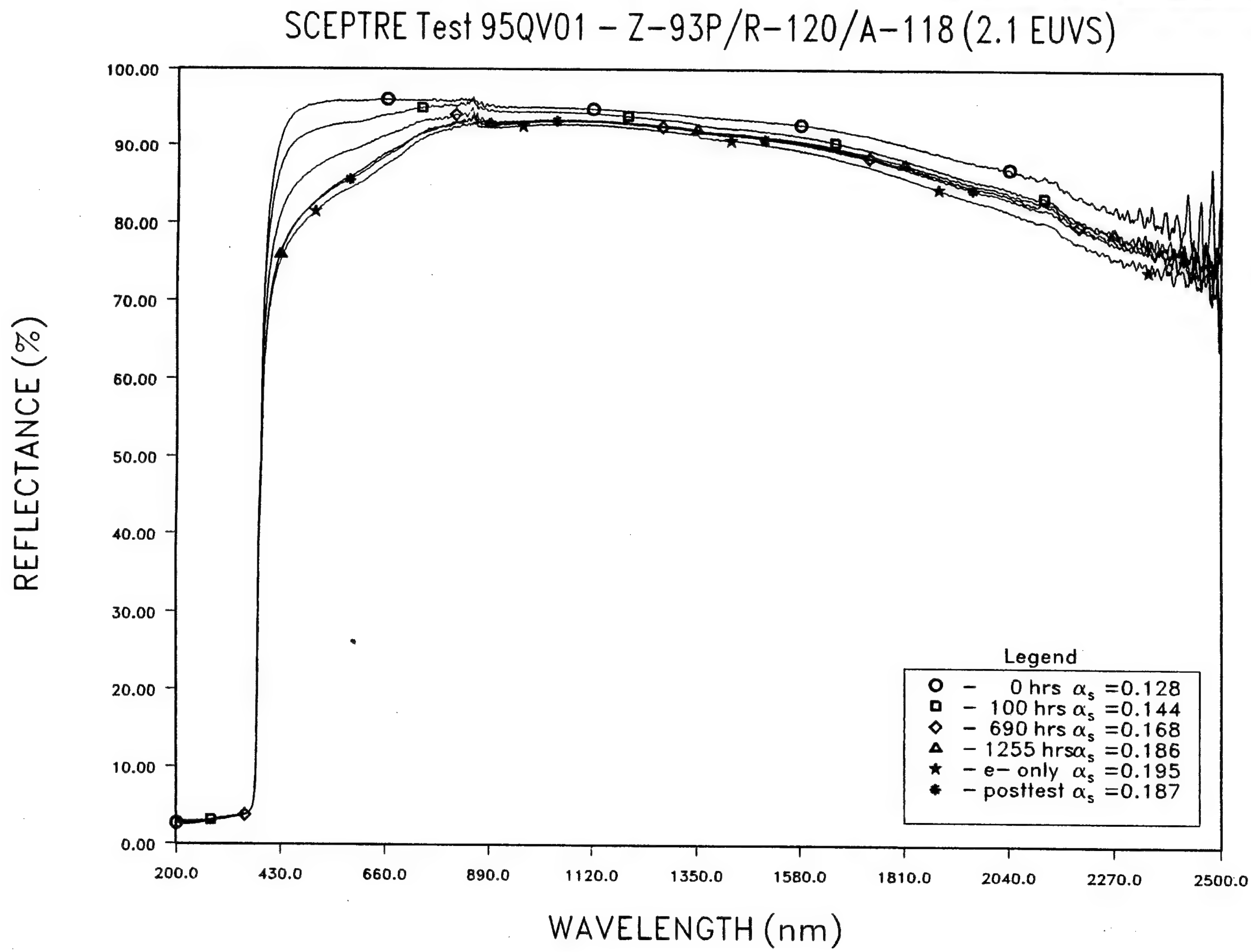

Figure D-7. SCEPTRE Test 95QV01 Z-93P (R-120) (2.1 EUVS) Reflectance Spectra History.

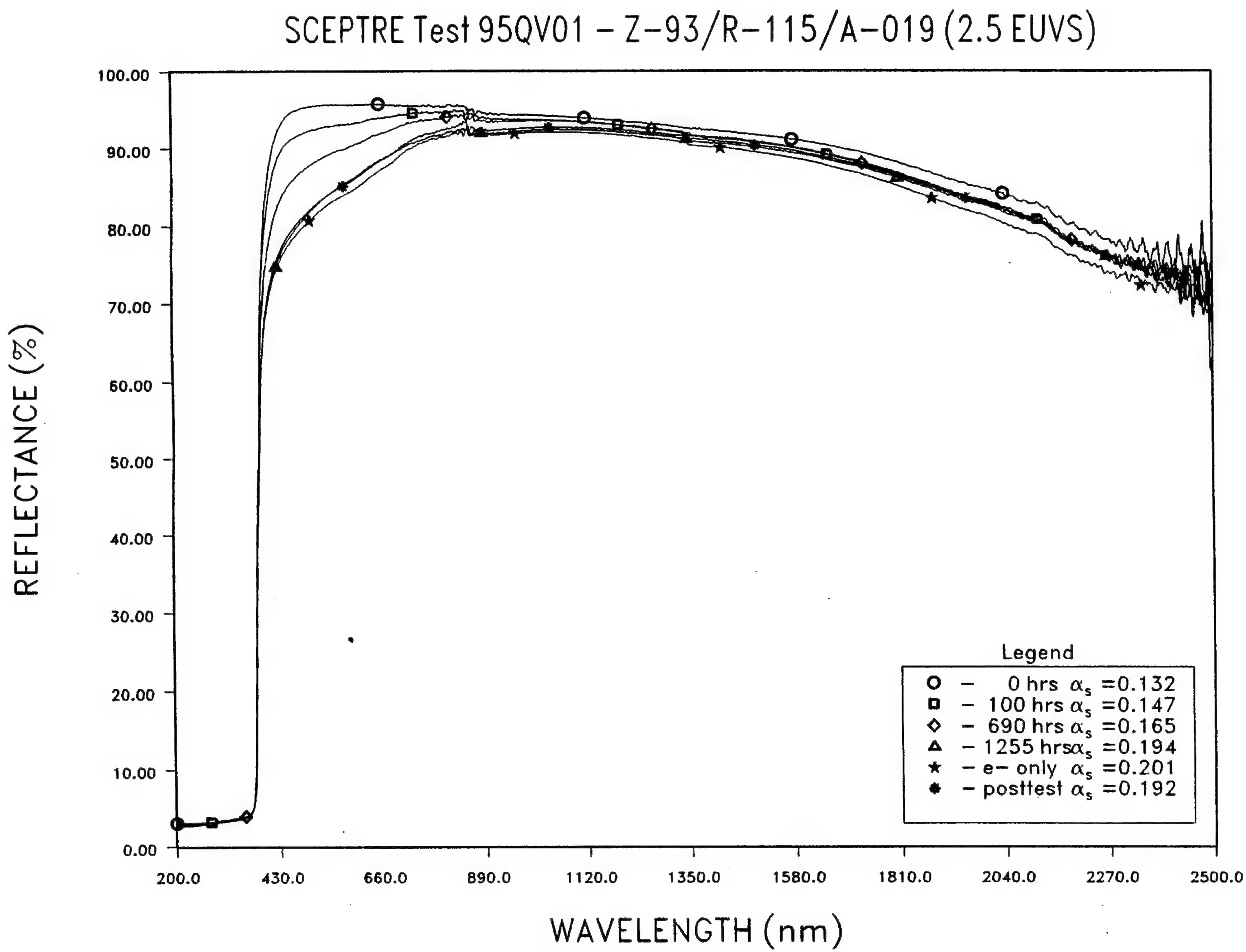

Figure D-8. SCEPTRE Test 95QV01 Z-93 (R-115) (2.5 EUVS) Reflectance Spectra History.

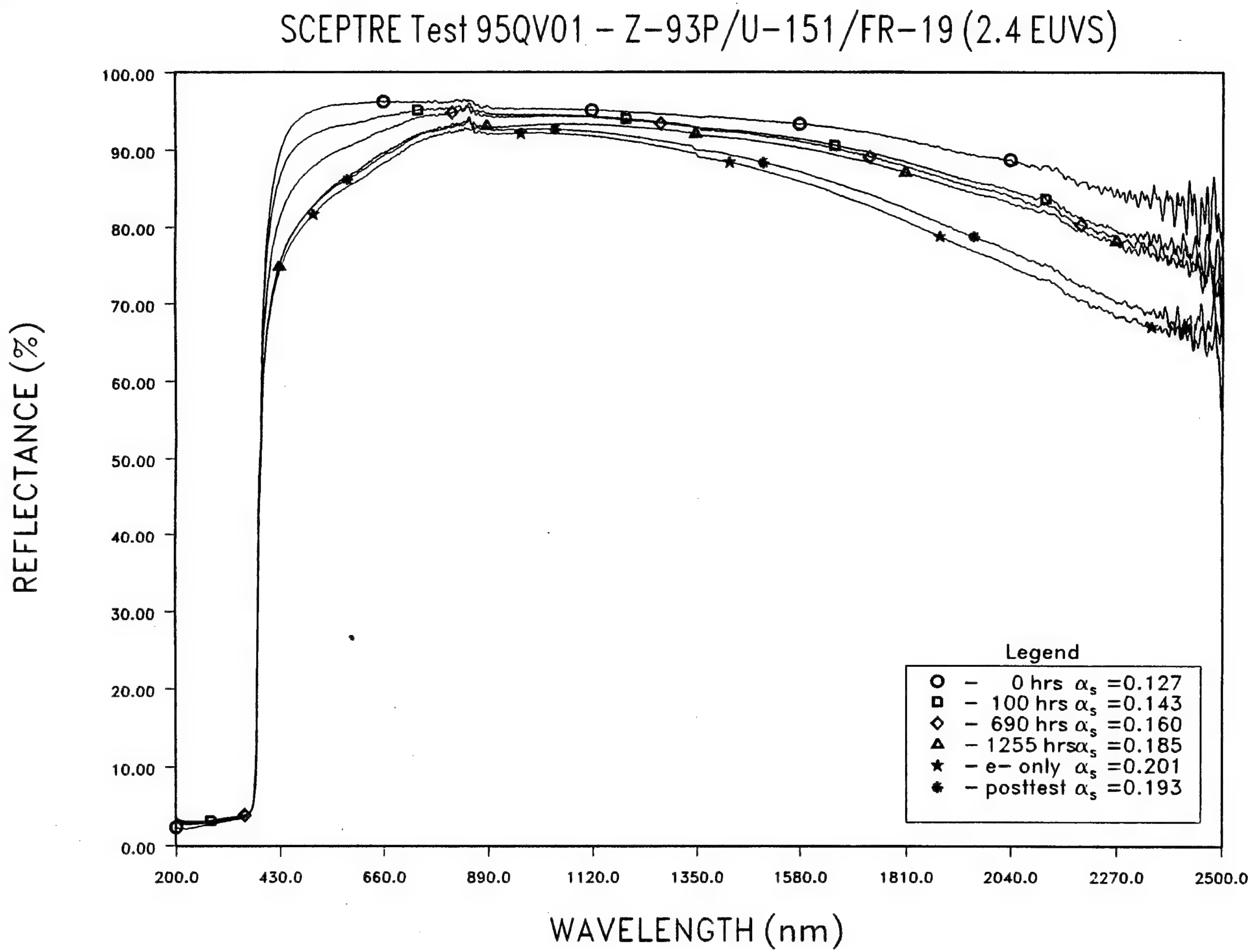

Figure D-9. SCEPTRE Test 95QV01 Z-93P (U-151) (2.4 EUVS) Reflectance Spectra History.

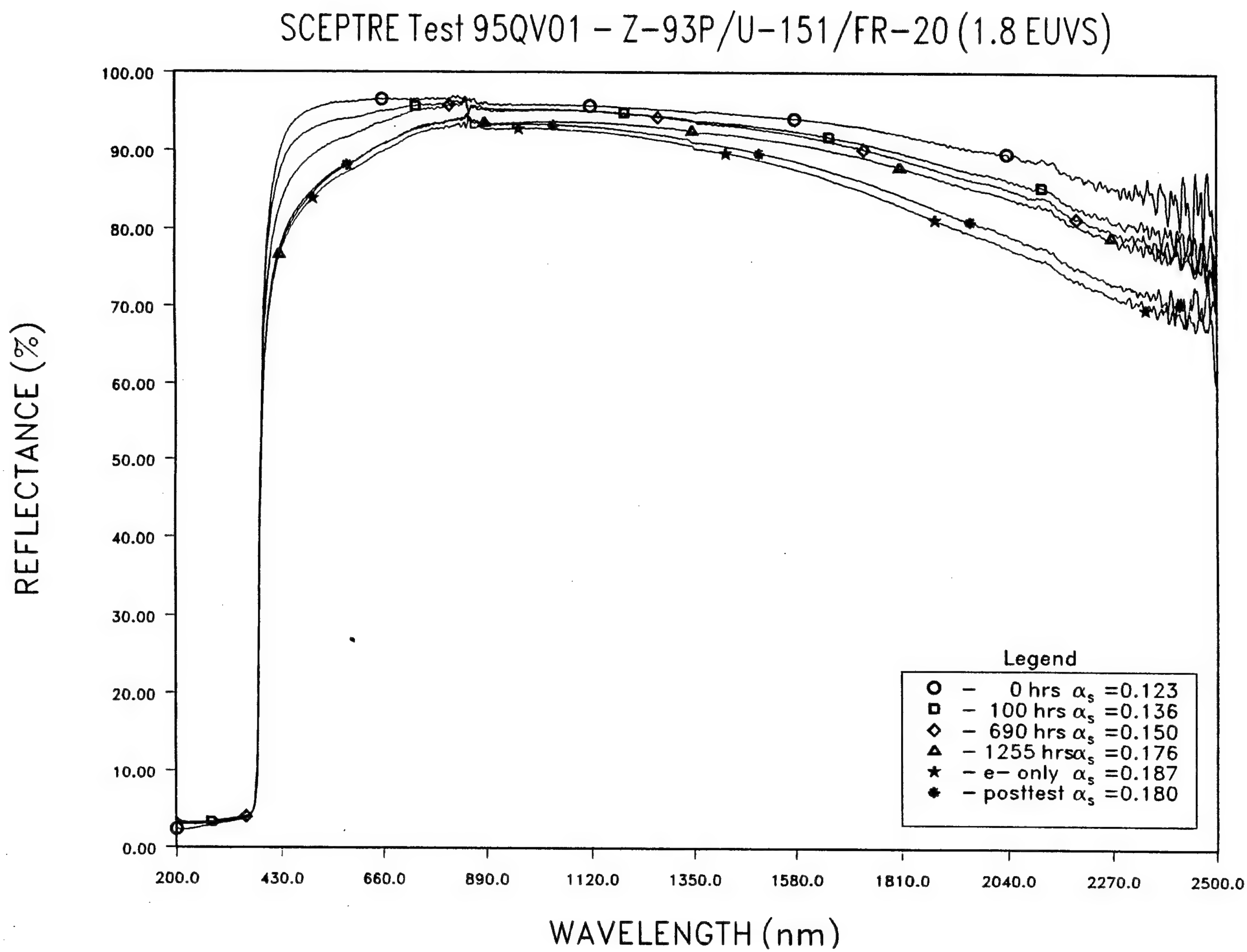

Figure D-10. SCEPTRE Test 95QV01 Z-93P (U-151) (1.8 EUVS) Reflectance Spectra History.

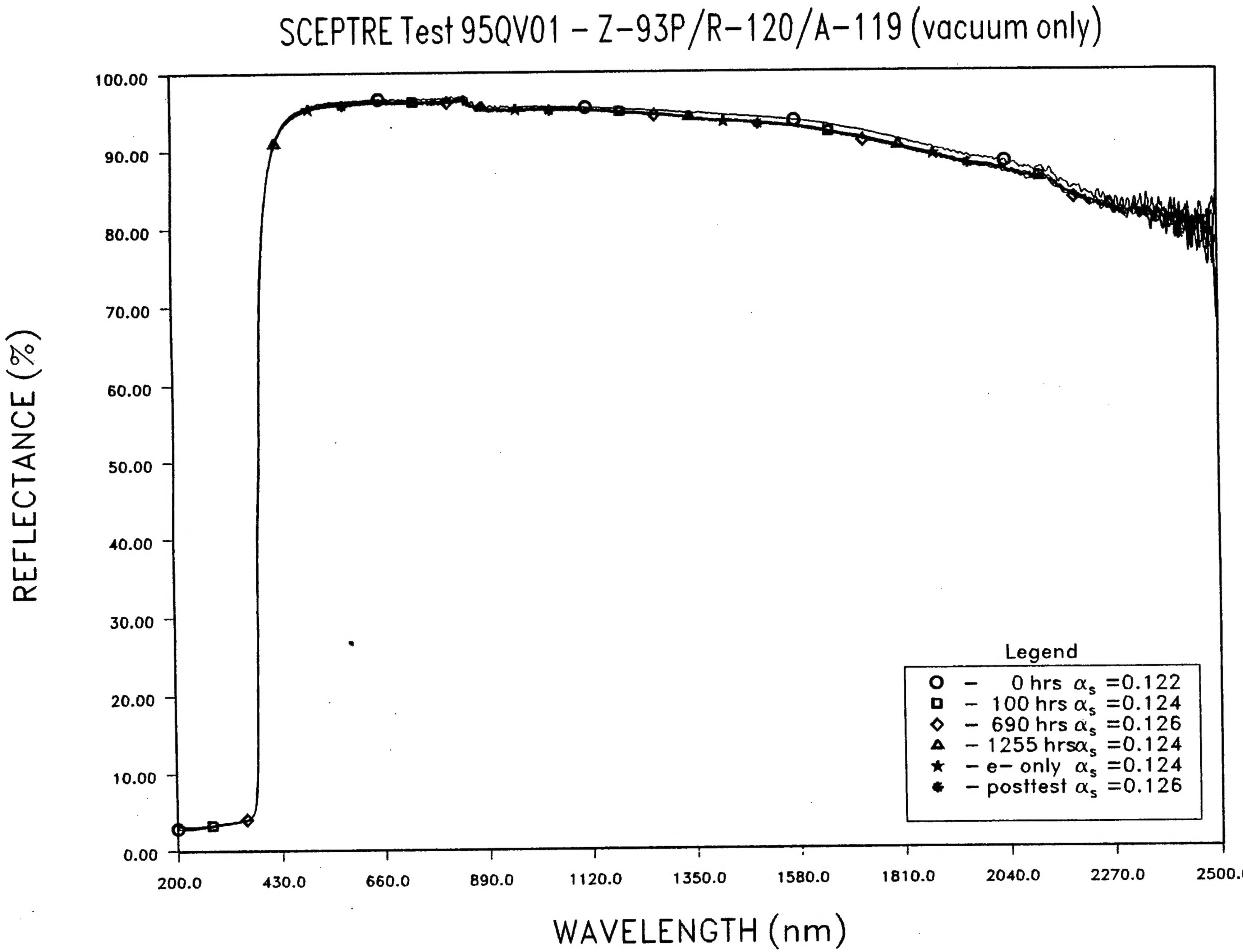

Figure D-11. SCEPTRE Test 95QV01 Z-93P (R-120) (reference) Reflectance Spectra History.

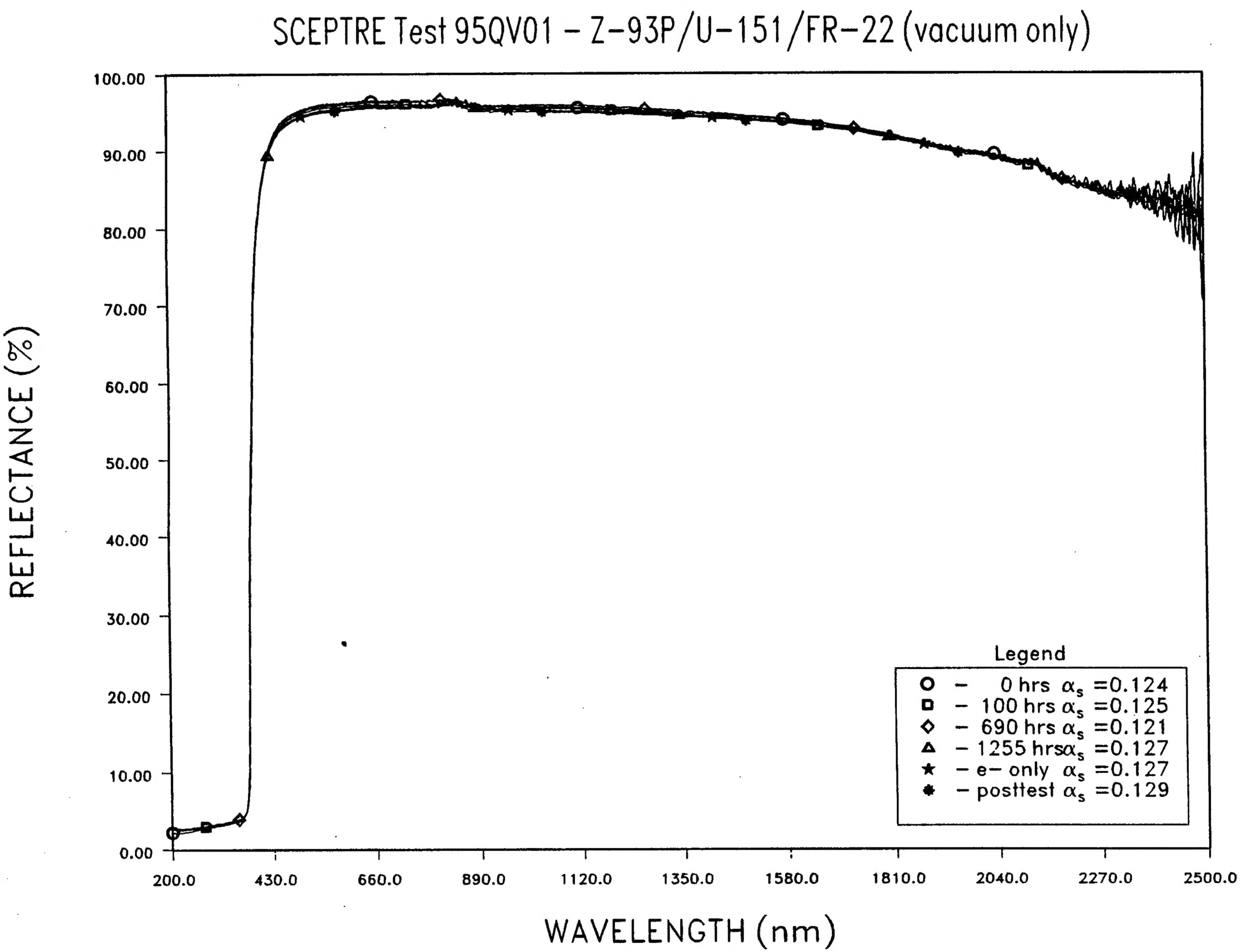

Figure D-12. SCEPTRE Test 95QV01 Z-93P (U-151) (reference) Reflectance Spectra History.

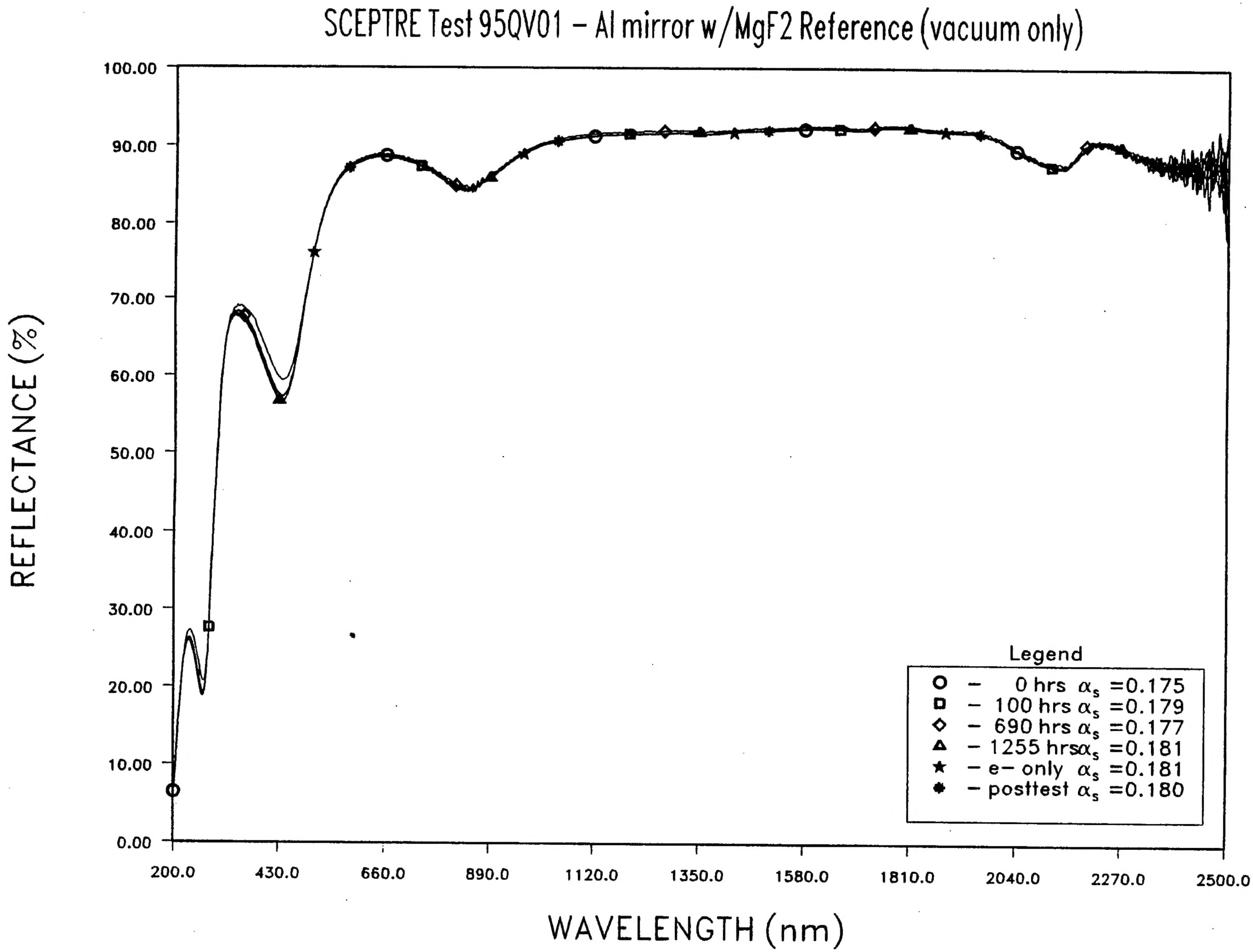

Figure D-13. SCEPTRE Test 95QV01 Al mirror w/MgF_2 (reference) Reflectance Spectra History.

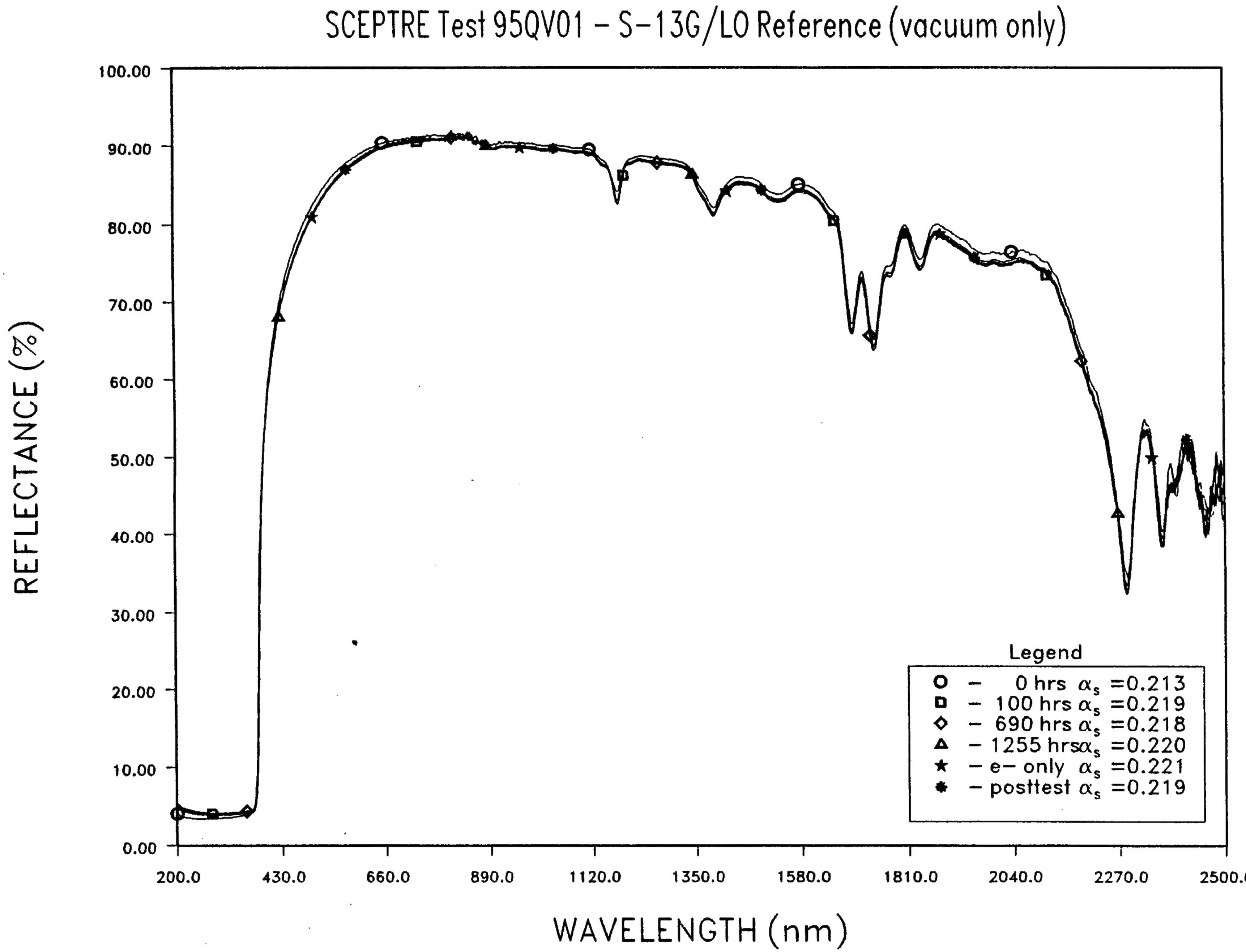

Figure D-14. SCEPTRE Test 95QV01 S-13G/LO (reference) Reflectance Spectra History.